



PHD

**Integrating Lean Construction, BIM and Quality: A New Paradigm for the Improvement of Chinese Construction Quality**

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**Integrating Lean Construction, BIM and Quality: A New  
Paradigm for the Improvement of Chinese Construction  
Quality**

Xingchen Zhang

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Architecture & Civil Engineering

February 2019

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## **Abstract**

Construction quality in China has often featured as an area requiring improvement. The question is, how could this be improved? One approach is to look at integrating lean construction ideas and BIM and to address their interactions. To date, no research has been conducted to comprehensively research the interactions of lean construction and BIM on improving construction quality.

The aim of this research was to investigate the feasibility of integrating lean construction and BIM on construction quality improvement in China and to develop a quality-based lean construction and BIM interaction framework during the construction phase. Five objectives were achieved by using a mixed method approach, comprising literature review, case studies, survey and framework development. The case studies were conducted with large, well-known, construction companies in China and the interviews were conducted with Chinese construction professionals. Analysis of the findings resulted in the development of a two-level framework. The key findings of this research reveal that lean construction could improve Chinese construction quality through 14 approaches and 14 BIM approaches could be used to improve Chinese Construction quality. Additionally, 4 general relationships between lean construction and BIM on their integration application to improve Chinese construction quality are presented in this research. Furthermore, a quality-based lean construction and BIM interaction framework is proposed to illustrate a new paradigm that provides an enriched understanding of how to use these interactions. The results contribute to the knowledge on construction quality, lean construction and BIM. The research findings also have practical implications for contractors working in China. The contractors could understand the practical issue when they practice lean construction and BIM on construction quality improvement. This research result could also be used as a guide book to provide a holistic view of integrated application between lean construction and BIM, and it provides a direction for the software developer to develop software and solve logical issues in software development.

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## **Table of Contents**

<b>Abstract.....</b>	<b>I</b>
<b>Acknowledgements.....</b>	<b>II</b>
<b>Table of Contents .....</b>	<b>III</b>
<b>List of Figures.....</b>	<b>VII</b>
<b>List of Tables .....</b>	<b>VIII</b>
<b>List of Abbreviations .....</b>	<b>X</b>
<b>Chapter 1: Introduction .....</b>	<b>1</b>
<b>1.1 Research Background .....</b>	<b>1</b>
<b>1.2 Research Justification .....</b>	<b>3</b>
<b>1.3 Research Aim and Objectives.....</b>	<b>4</b>
<b>1.4 Scope of Research .....</b>	<b>4</b>
<b>1.5 Research Methods Overview .....</b>	<b>6</b>
1.5.1 Literature review .....	6
1.5.2 Case studies .....	6
1.5.3 Survey.....	6
1.5.4 Framework development .....	6
1.5.5 Framework validation.....	7
<b>1.6 Thesis Structure .....</b>	<b>7</b>
<b>Chapter 2: Literature Review .....</b>	<b>9</b>
<b>2.1 Introduction.....</b>	<b>9</b>
<b>2.2 Historical Review of Construction Quality .....</b>	<b>9</b>
2.2.1 Understanding construction quality.....	9
2.2.2 The current situation of Chinese construction quality .....	12
2.2.3 The current Chinese construction quality improvement requirements .....	16
<b>2.3 Historical Review of Lean Construction Ideology .....</b>	<b>22</b>
2.3.1The emergence and development of lean construction.....	22
2.3.2 Definition and principles of lean construction.....	25
2.3.3 The potential use of lean construction to improve construction quality .....	31

<b>2.4 Historical Development and Current Researches of BIM .....</b>	<b>43</b>
2.4.1 Historical development of BIM.....	43
2.4.2 Definition and advantages of BIM .....	47
2.4.3 The potential of a BIM driven approach for quality improvement.....	50
<b>2.5 Current Research on the Integration of Lean Construction and BIM on Construction Quality Improvement Aspects.....</b>	<b>67</b>
<b>2.6 Summary .....</b>	<b>69</b>
<b>Chapter 3: Research Methodology .....</b>	<b>71</b>
<b>3.1 Introduction.....</b>	<b>71</b>
<b>3.2 Research Philosophy.....</b>	<b>71</b>
3.2.1 Ontology .....	72
3.2.2 Epistemology .....	72
<b>3.3 Research Approaches .....</b>	<b>73</b>
3.3.1 Quantitative research .....	73
3.3.2 Qualitative Research.....	73
3.3.3 Mixed methods research.....	74
<b>3.4 Research Design and Data Collection Techniques.....</b>	<b>75</b>
3.4.2 Data Collection Techniques in Case Studies .....	79
3.4.3 Data Collection Techniques in Surveys.....	84
<b>3.5 Timeline of Research .....</b>	<b>86</b>
<b>3.6 Adopted Research Methods .....</b>	<b>87</b>
3.6.1 Literature review .....	87
3.6.2 Case studies .....	88
3.6.3 Survey.....	100
3.6.4 Framework development .....	103
3.6.5 Framework validation.....	104
<b>Chapter 4: Case Study Results .....</b>	<b>107</b>
<b>4.1 Introduction.....</b>	<b>107</b>
<b>4.2 Case Study Findings for Project TZ .....</b>	<b>108</b>
4.2.1 The background of the project.....	108
4.2.2 Quality-based lean construction theories and techniques .....	109

4.2.3 Incentives, limitations and requirements of quality-based lean construction .....	119
4.2.4 Findings discussion of Project TZ.....	124
<b>4.3 Case Study Findings for Project LX .....</b>	<b>132</b>
4.3.1 The background of the project.....	132
4.3.2 Quality-based BIM applications .....	133
4.3.3 The incentives, limitations and requirements of quality-based BIM.....	138
4.3.4 Findings discussion of project LX.....	140
<b>4.4 The Discussion of Feasibility of Integrating Lean Construction and BIM to Improve Chinese Construction Quality through Case Study Results.....</b>	<b>149</b>
<b>4.5 Summary .....</b>	<b>153</b>
<b>Chapter 5: Survey Results.....</b>	<b>155</b>
5.1 Introduction.....	155
5.2 The Importance of Integrating Lean Construction and BIM to Improve Construction Quality .....	155
5.3 The Exploration of the Quality-based Interactions between Lean Construction and BIM.....	155
5.3.1 The strategical interactions between quality-based lean construction theories and quality-based BIM mechanisms.....	155
5.3.2 The implementation interactions between quality-based lean construction techniques and quality-based BIM applications .....	162
5.4 Discussion of Findings from Survey .....	169
5.5 Summary .....	172
<b>Chapter 6 Discussion and Framework Development .....</b>	<b>174</b>
6.1 Introduction.....	174
6.1 Quality-based Lean Construction and BIM Interaction Framework Discussion and Development .....	174
6.2 Quality-based Lean Construction and BIM Interaction Framework Validation .....	183
6.2.1 Framework validation process.....	183
6.2.2 Results of quality-based lean construction and BIM interaction framework validation interviews .....	184
6.3 Interaction Framework Implementation Strategy .....	191

6.4 Summary .....	195
<b>Chapter 7: Conclusion .....</b>	<b>197</b>
7.1 Introduction.....	197
7.2 Achievement of the Research Aim and Objectives .....	197
7.3 Research Contributions to Knowledge .....	201
7.4 Research Limitations.....	202
7.5 Recommendations for future Research .....	203
<b>Reference.....</b>	<b>205</b>
<b>Appendix.....</b>	<b>233</b>



**List of Figures**

Figure 1: The percentages of companies in North America using BIM in 2007, 2009 and  
2012 ..... 45

Figure 2: Levels of BIM ..... 46

Figure 3: Benefits of BIM Process..... 49

Figure 4: Interview Process Flow Chart ..... 99

Figure 5: LC-BIM Quality Improvement House ..... 193

## List of Tables

Table 1: The Scope of Research .....	5
Table 2: The Requirements of Current Construction Quality Improving Summarised from the Existing Literature .....	16
Table 3: Comparison Between Mass Production and Lean Production.....	23
Table 4: The Theory of TFV .....	28
Table 5: Waste in the Construction Industry .....	29
Table 6: Potential Quality-based Lean Construction Theories Summarised from the Existing Literature.....	35
Table 7: Potential Quality-based Lean Construction Techniques Summarised from the Existing Literature .....	39
Table 8: Potential Quality-based BIM Mechanisms Summarised from the Existing Literature .....	56
Table 9: Potential Quality-based Lean Construction Theories Summarised from the Existing Literature.....	62
Table 10: Potential Quality-based Interactions between Lean Construction and BIM Summarised from the Existing Literature.....	69
Table 11: Summary of Research Methodology .....	71
Table 12: Characteristics of Case Studies.....	78
Table 13: Types of Case Study Evidence .....	80
Table 14: Comparison between Questionnaires and Interviews .....	85
Table 15: Interviewees in Survey.....	102
Table 16: List of the Interviewees for Company ZJ .....	109
Table 17: Quality-based Lean Construction Theories Identified in Project TZ.....	109
Table 18: Quality-based Lean Construction Techniques Identified in Project TZ .....	109
Table 19: Quality-based Lean Construction Theories from the Literature Review and the Case Study .....	124
Table 20: Quality-based Lean Construction Techniques from Literature Review and Case Study .....	128

Table 21: List of the Interviewees for Company HY .....	132
Table 22: Quality-based BIM Applications Identified in Project LX .....	133
Table 23: Potential Quality-based BIM Mechanisms from Literature Review and Case study .....	141
Table 24 Quality-based BIM Applications from the Literature Review and the Case Study .....	144
Table 25: The quality-based Strategical Interactions from Survey .....	156
Table 26: The quality-based implementation interactions from survey .....	163
Table 27: The Quality-based Strategical Interactions between Lean Construction Theories and BIM Mechanisms .....	169
Table 28: The Quality-based Implementation Interactions between Lean Construction Techniques and BIM Applications .....	170
Table 29: Interaction Matrix of Lean Principles and BIM Functionalities .....	176
Table 30: Strategic Interaction Matrix of Quality-based Lean Construction Theories and Quality-based BIM Mechanisms .....	178
Table 31: Strategic Interaction Matrix: Explanations of Cell Contents .....	179
Table 32: Implementation Interaction Matrix of Quality-based Lean Construction Techniques and Quality-based BIM Applications .....	181
Table 33: Implementation Interaction Matrix: Explanations of Cell Contents .....	182
Table 34: Interviewees in Framework Validation .....	184
Table 35: Validated Strategic Interaction Matrix of Quality-based Lean Construction Theories and Quality-based BIM Mechanisms .....	186
Table 36: Validated Strategic Interaction Matrix: Explanations of Cell Contents .....	187
Table 37: Validated Implementation Interaction Matrix of Quality-based Lean Construction Techniques and Quality-based BIM Applications .....	189
Table 38: Validated Implementation Interaction Matrix: Explanations of Cell Contents ...	190

## List of Abbreviations

BIM	Building Information Modeling
CAD	Computer-Aided Design
CE	Concurrent Engineering
GDP	Gross Domestic Product
IPD	Integrated Project Delivery
IGLC	International Group of Lean Construction
TPS	Japanese Toyota Production System
JIT	Just-In-Time
LPS	Last Planner System
LCI	Lean Construction Institute
LiDAR	Light Detection and Ranging
LLR	Log-Likelihood Ratio
MEP	Mechanical, Electrical, and Plumbing
MOHURD	Ministry of Housing and Urban-Rural Development
PDCA	Plan, Do, Check and Action
PPC	Percent Plan Complete
POP	Product, Organisation and Process
SMVs	Standardised Model Views system
TLS	Terrestrial Laser Scanning
TQM	Total Quality Management
TFV	Transformation, Flow and Value generation
NBIMS-US	US National Building Information Model Standard
WOS	Web of Science
WTO	World Trade Organization

## **Chapter 1: Introduction**

### **1.1 Research Background**

With the rapid development of the economy, the Chinese construction industry, as a pillar of China's national economy, has also developed at an unprecedented rate (Wei and Lin, 2004). By 2016, China's gross domestic product (GDP) of the construction industry had reached 19.35 trillion yuan, which accounted for 6.66% of the country's GDP (Sinchew, 2017). The number of employees in the Chinese construction industry also reached 61,576,100 in 2017 (CEIC, 2018). However, while the Chinese construction industry is big, it is not strong, especially in terms of quality (Liu, 2016). The construction quality in the construction industry seems to be a problem for every country (Guan and Li, 2011), but the problems facing China are particularly serious (Wang, 2013). The frequent occurrence of accidents related to quality issues in China has caused a great loss of life and property. A total percentage of 46% of customers claim that they are suffering from quality defect problems (Xinhua, 2013). In order to solve the quality problems, the Chinese government changed the construction quality management mode from inspection quality management to statistic quality management and then to total quality management (Zhang, 2008; Zhang, 1999; Zeng et al., 2003; Shen and Chen, 2015). However, the quality of construction is still not satisfactory (Ou, 2012). The Chinese government has also made many attempts to improve the construction quality in recent years, such as introducing BIM and lean construction. Clash detection, as one of the functions of BIM, has been widely implemented to improve construction quality in China (Liu, 2016). Additionally, some philosophies that embody lean construction have been applied in China for several years to solve quality problems (Wen, 2000). Good construction quality refers to eliminate defects, deliver value to the customer and meet the expectations of the customer. The improvement of construction quality in China lies in these aspects. These will be discussed in detail in Section 2.2.1.

Lean construction is a continuous process of meeting or exceeding the needs of all customers, eliminating waste and pursuing value (Dickmann et al., 2004). Lean construction, with its origins in the Japanese Toyota Production System (TPS), is now widely used all over the world. Although lean construction has been developing for

many years, it has just started to become popular in China (Tan, Xia and Yang, 2014). However, the degree of application of lean construction in China varies (Ou, 2012). Some companies have already accumulated experience of successful implementation, while others have just started to use this process (ibid.). Attempts have been made in the last few years to use some lean theories to guide the improvement of construction quality in China.

Studies in the field of lean construction indicate that the majority of the current lean construction researches focus on project management, cost, performance measurement, implementation, design management and the customers (Alves and Tsao, 2007). However, quality has received the least attention in the research on lean construction. Only 0.7% of studies on lean construction published between 2000 and 2006 focused on lean construction and construction quality, accounting for a very small proportion (ibid.). Furthermore, the researches that have investigated quality in lean construction are not thorough. Although there is a consensus in the existing literature (Misfeld and Bonke, 2004; Marosszeky et al., 2002; Liu and Shi, 2017) that lean construction benefits the improvement of construction quality. There is a lack of comprehensive researches on the interaction aspects, especially in the construction phase.

BIM is an emerging construction technique that helps to design and construct buildings digitally. According to Sacks, Radosavljevic and Barak (2010), BIM is a form of parametric objective modelling which can display construction information and conduct simulations. It is convenient to conduct a virtual construction of what will be built on site (Azhar et al., 2008). Although BIM has only emerged in China in recent years, there is no doubt that BIM has received great attention in China (Liu et al., 2017). According to a report produced in 2013, about 55% of construction companies had heard about BIM, but less than 15% of construction companies used BIM in their projects (Chinese Construction Industry Association, 2013). However, by 2016, the percentage of projects applying BIM in China was about 40% (Lu, 2018). According to the relevant documents from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (2015), by the end of 2020, the percentage of new projects using integrated BIM will reach 90%. At present, some

functions of BIM are tentatively applied in the improvement of construction quality.

Similar to lean construction, BIM research has been widely conducted in various fields. The research areas of construction costs, schedules and energy performance are popular topics (He and Li, 2013). However, few researchers have investigated the role of BIM in improving quality. The findings of the existing studies in the field are mainly related to the potential application of BIM with integrating specific techniques, such as 3D laser scanning and AR techniques (Kim et al., 2015; Becerik-Gerber et al., 2011; Wang et al., 2016; Park et al., 2013; Kwon et al., 2014). There is still a lack of research to instruct the general interactions between BIM and construction quality improvement during the construction phase, which the researches related to quality only account for 5% of all BIM-related articles from 2006-2013 (Ding, Zhou and Akinci, 2014).

## **1.2 Research Justification**

Generally, the Chinese construction industry has suffered a lot for the poor construction quality (which refers to existing defects, not deliver value to the customer and not meet the expectations of the customer). How to improve Chinese construction quality is a big challenge. The previous research results have illustrated that lean construction and BIM can play positive roles in improving construction quality respectively (Misfeld and Bonke., 2014; Marosszeky et al., 2002; Kim et al., 2015; Park et al., 2013; Wang et al., 2015). However, separately applications of lean and BIM are not panaceas for solving all construction quality problems. Integrating lean construction and BIM together is better than separate use. However, there exists a gap in investing quality-based interactions between lean construction and BIM, especially in the construction phase. The current research on integrating lean construction and BIM mainly focus on design management, integrated framework, visual management and building information. However, there is no doubt that quality is ignored, especially in the construction phase. Very few researches are identified on this topic. The importance of integrating lean construction and BIM to improve the construction quality is confirmed by some researches (Liu and Shi, 2017; Laine, Alhava and Kiviniemi, 2014). However, there remains a research gap on the aspects of interactions between lean construction and BIM on construction quality improvement, not to

mention in the context of the Chinese construction phase. Understanding quality-based interactions could provide the foundations for investigating how to integrate lean construction and BIM to improve Chinese construction quality. Therefore, further efforts are needed to bridge this gap in knowledge. These are the incentives of doing this research on investigating the interactions of lean construction and BIM on construction quality improvement aspect. The research is limited to the construction phase due to the research should be focused on one phase and the interactions in construction phased is not mentioned before.

### **1.3 Research Aim and Objectives**

The research question is what are the interactions between lean construction, BIM and Chinese construction quality. The aim of this research is to develop a quality-based lean construction and BIM interaction framework for the construction phase. In order to achieve this aim, the following six objectives are proposed:

- (1) To explore and synthesise the current Chinese quality improving requirements
- (2) To investigate the quality-based lean construction approaches and quality-based BIM approaches
- (3) To analyse the feasibility of integrating lean construction and BIM to improve construction quality through Chinese quality improvement requirement perspective
- (4) To explore the potential interactions between quality-based lean construction approaches and quality-based BIM approaches.
- (5) To develop and validate the interaction framework of lean construction and BIM on Chinese quality improvement

### **1.4 Scope of Research**

Based on the above discussion regarding research justification, the scopes of research are presented in Table 1



Table 1: The Scope of Research

Research Scope	Reasons
The research is limited on investigating quality-based interactions between lean construction and BIM on the Chinese construction phase	<ul style="list-style-type: none"> <li>• The construction phase is a key phase in achieving of construction quality improvement</li> <li>• There lacks systematic exploration of the interactions of lean construction and BIM to improve construction quality in the construction phase</li> <li>• The Chinese construction industry is plagued by quality problems, and construction quality in China is urgently needed to be improved. However, little interaction research has been conducted in the context of China</li> <li>• The scope of research needs to be narrowed down due to time constraints</li> </ul>
The research is limited to identify comprehensive quality-based interactions between lean construction and BIM on Chinese construction phase, rather than especially investigate the detailed implementation of each interaction in-depth	<ul style="list-style-type: none"> <li>• According to the research question of what the interactions between lean construction, BIM and Chinese construction quality, this research needs to conduct comprehensive research to support a holistic view of the quality-based interactions</li> <li>• The general and comprehensive quality-based interactions between lean construction and BIM on Chinese construction phase provide the foundation for in-depth research on each interaction. This research should mainly focus on comprehensive interactions</li> </ul>
The research is limited in focusing on large construction companies in China	<ul style="list-style-type: none"> <li>• Lean construction and BIM are not widely adopted in China. Only large Chinese construction companies have tried to apply them. The experts on lean construction and BIM are mainly from large Chinese construction companies</li> </ul>

## **1.5 Research Methods Overview**

### **1.5.1 Literature review**

A comprehensive literature review was conducted which mainly aimed to investigate Chinese quality improvement requirements, quality-based lean construction approaches, quality-based BIM approaches and the integrations between lean construction and BIM to improve construction quality in existing literature. Citespace as an auxiliary literature review tool was adopted to help author conduct literature review. The findings obtained from the literature review are benefited to establishing a clear direction for data collection. Moreover, according to the literature review, there lacks research on integrating lean construction and BIM to improve construction quality.

### **1.5.2 Case studies**

Case studies were conducted to achieve the objectives 2 which to investigate the quality-based lean construction approaches and quality-based BIM approaches. Two well-known Chinese construction companies were selected as case companies. The observation, interviews and documentation were selected as data collection techniques. At the end of case studies, 9 potential quality-based lean construction approaches and 7 quality-based BIM approaches were identified.

### **1.5.3 Survey**

The semi-structured interviews were employed to investigate the quality-based interactions between quality-based lean construction approaches and quality-based BIM approaches. 22 interviewees participated in this research. At the end of interviews, 28 quality-based interactions between lean construction approaches and BIM approaches were identified. The result of interviews provided a basis of developing an interaction framework.

### **1.5.4 Framework development**

The quality-based lean construction and BIM interaction framework were developed through analysing findings from literature review, case studies and interviews. The quality-based lean construction and BIM interaction framework consisted of two

levels, which were: strategic level and implementation level. The strategic level framework aimed to present the interactions between quality-based lean construction theories and quality-based BIM mechanisms. The implementation level framework aimed to present the interactions between quality-based lean construction techniques and quality-based BIM applications.

#### **1.5.5 Framework validation**

The quality-based lean and BIM interaction framework validation was designed to validate the accuracy and completeness of the framework. 10 interviewees participated in the validation interviews. The results of validation are presented in Chapter 6.

### **1.6 Thesis Structure**

**Chapter 1** provides a background information and research justification of this research. The research and objectives are also identified and explained in this chapter. The scope of research and overview of research methods are presented at the end of the chapter.

**Chapter 2** provides a detailed review of the research context and focuses on integrating lean construction and BIM to improve construction quality.

**Chapter 3** provides a detailed description of research methods. The justifications of research design and data collection techniques, and detail data collection process are discussed in this chapter.

**Chapter 4** describes the findings from case studies. The potential quality-based lean construction approaches and quality-based BIM approaches are identified from the case study. Moreover, incentives, limitations and requirements of quality-based lean construction approaches and quality-based BIM approaches are investigated and discussed.

**Chapter 5** presents the findings from survey results. The potential quality-based interactions between lean construction and BIM are identified through the survey.

**Chapter 6** discusses the finding from literature review, case study and survey. Analysing these findings confirms the feasibility of integrating lean construction and BIM to improve Chinese construction quality, and results in a two-level quality-based lean construction and BIM interaction framework. The interaction framework is validated in this chapter, and then a new construction quality improvement paradigm for the Chinese construction industry is proposed and recommended by analysing framework.

**Chapter 7** concludes how the research findings help to achieve research objectives. Moreover, the research contributions and research limitations are discussed. The recommendations for industry and future researchers are given at the end of this chapter.

## **Chapter 2: Literature Review**

### **2.1 Introduction**

The literature review findings of construction quality, lean construction and BIM are presented in this chapter. The first section identifies the Chinese construction quality improvement requirements through a comprehensive review of construction quality management development. The second section is to investigate the potential uses of lean construction to improve construction quality. The third section finds out potential BIM driven approaches for quality improvement. The fourth section detail reviews the current research on integrating lean construction and BIM to improve construction quality.

### **2.2 Historical Review of Construction Quality**

#### **2.2.1 Understanding construction quality**

To improve construction quality, the meaning of quality needs to be understood. Giving a clear definition of quality seems to be the first step of understanding quality, but this is not easy. Quality is subjective, perceptual and conditional (Berard, Vestergaard and Karlshøj, 2012). Compared with the assessment of whether a project has been delivered within budget and to schedule, the judgement of quality is less obvious. The judgement of quality is also easily deceived by appearances, and different researchers from different backgrounds can have different views of quality. Providing a reasonable definition of quality has long been a focus of researchers. Over the years, various definitions have been given by different construction experts and scholars in different contexts (Giaccio, Canfora and Signore, 2013), but none of these definitions can be universally accepted (Janipha and Ismail, 2013).

Juran (1979) defines quality as fitness for use. Juran and De Feo (2010) develop the previous definition of fitness for use to fitness for purpose. According to Arditi and Gunaydins' definition (1997), 'quality can be defined as meeting the functional requirements, legal, and aesthetic of a project'. Arditi and Gunaydins explain that quality is ensured only in the situation that all three requirements are fulfilled. Moreover, ISO 9000 is accepted as an international standard of certification of quality management systems. Therefore, quality is also regarded as conformance to the ISO

9000 criteria in some researchers' reports (Bubshait and Al-Atiq, 1999; Sun, 1999). As time passes, the definitions of quality have been evolved.

After reviewing the relevant definitions of quality, it is worth noting that the definitions of quality that are listed below have many supporters.

Crosby (1979), one of the most well-known quality management researchers in the last century, defines quality as the presence of zero defects. The construction process does not need to be perfect but needs to be zero defects. This definition is frequently quoted by other researchers (Wang, 2012).

Feigenbaum (1951) presents a value-based definition of quality:

Quality does not have the popular meaning of 'best' in any absolute sense. It means best for certain customer conditions. These conditions are the actual use and the selling price of the product. Product quality cannot be thought of apart from product cost.

Feigenbaum believes that quality is delivering value to the customer.

Conformance to specifications is also a crucial quality definition that has already been accepted by many construction companies (Chen and Luo, 2014). As the research aim is to improve Chinese construction quality, according to the government publications (Chinese State Department, 2010), construction projects quality first needs to conform to Chinese national laws, construction codes and specifications.

Deming (1986) believes that quality can only be defined by the customer. The criteria which decides good quality could change with the customers' expectations. Torbica and Stroh (1999) share a similar view to Deming and conclude that quality is the meeting of the expectations of the customer. Torbica and Stroh explain the importance of meeting the customers' requirements and assert that quality can only be judged by the customer. Other researchers like Gronroos (1983) and Parasuraman, Zeithaml and Berry (1985) also agree that meeting the customers' expectations is a criterion of good quality.

Different definitions are given at different times based on different circumstances and different researchers' backgrounds. No one current definition can be seen as completely valid in any situation. According to the literature review results, the last four definitions are most frequently referenced. Although these four definitions are widely accepted, some limitations still exist.

Defining quality as zero defects sounds valid, but it is not comprehensive. The voice of the customers is also worth hearing and certain specifications need to be considered (Crosby management institute, 2014). It is difficult to confirm that a construction process with zero defects is good quality if the customer requirements are ignored and specifications are not complied.

Limiting the definition of quality to value may not be applicable in all situations. A plan that over considers time and cost may not deliver quality. Sometimes, quality is achieved at all costs. For example, the Chinese government aimed to host an impressive Olympic Games in Beijing in 2008 at all costs (Rui, 2008). The first consideration in the construction of the Olympic venues was how to make them perfect, rather than the construction costs (ibid.). Value seems to be only one aspect of quality criteria.

It seems to be a one-sided understanding to only consider quality as conformance to specifications. Indeed, conforming to specifications is the prerequisite of judging the quality of a construction project in China (Shen and Chen, 2015) but it is not the only consideration. The specifications required by the government are merely the minimum standard needed for the construction quality. Even if a project conforms to specifications, it may not reach the quality levels that the customers require (Ou, 2012). The quality expected by the customers may be far beyond the specifications. The customers' requirements should also be considered.

Meeting customers' requirements seems to be a future trend in improving construction quality (Giaccio, Canfora and Signore, 2013), which is accepted by a large number of

researchers. It should be the customers, rather than the designers or contractors, that determine whether a building's quality is acceptable (Sowards, 2013). This definition seems to be widely accepted (Ou, 2012; Sowards, 2013; Giaccio, Canfora and Signore, 2013), but the definition of the customer needs to be explored. The customer should not be narrowly defined as the owner or the final user. The government is also a kind of customer whose requirements also need to be satisfied (Wang, 2012). The government's construction requirements are presented as various national construction specifications. Additionally, more specifically, the workers throughout the whole construction process are also a kind of customer. The outcome of the initial work should meet the requirements of the next step in the work's process. The workers in the next construction step are customers of the workers in the previous step of the process (Cui, 2016).

Some drawbacks still exist in this definition from Giaccio, Canfora and Signore (2013). Firstly, one drawback is that this kind of definition is difficult to measure. The customers' requirements could change frequently. The second drawback is that some customers lack expertise, so some of their requirements could be ill-advised, resulting in dangerous construction. Following the customers' requirements strictly seems infeasible.

It is wise to define good quality in a broad and wide-ranging way. In this research, good construction quality is seen as eliminating defects which can deliver value to the customer and to meet the expectations of the customer. The improvement of construction quality in China lies in these aspects.

## **2.2.2 The current situation of Chinese construction quality**

### **2.2.2.1 Construction is a pillar industry in China**

The construction industry is considered a significant contributor to economic growth in many countries (Nawaz and Ikram, 2013). It strongly influences the GDP growth rate, and this situation is especially apparent in China (Gui, 2013). China has been experiencing an economic boom in the decades since it carried out a reform and opening-up policy in 1978 (Thim and Chen, 2004). Construction has become a pillar industry of China's national industry, and the current growth of China's GDP mainly



relies on the development of the construction industry (Wei and Lin, 2004). As the backbone of China's economy, the Chinese government and construction companies have made significant investments in the construction industry (Ou, 2012). China has developed into the largest construction market in the world, which benefits China's rapid economic development (Sjoholt, 1997). According to the National Bureau of Statistics of China, the Chinese construction industry in 2000 was valued at US\$71.5 billion (Thim and Chen, 2004). The White Paper from Autodesk (Autodesk, 2007) also reported that 'China was spending over \$375 billion a year on construction (16% of its GDP) and consumed 55% of the World's production of concrete, 36% of the World's steel and 30% of the world's coal in 2004'. Moreover, the Chinese construction industry consumed 6.6 gigatons of concrete from 2011 to 2013 which is more than the U.S. used in the entire 20<sup>th</sup> century (Diaz, 2015). Recent statistics show the increased proportion of construction account for Chinese GDP was 6.9% in 2015 and the number of employees in the Chinese construction industry was 50 million and 30 thousand (Ernst and Young, 2016). Although these percentages look promising for China's construction industry, they only focus on the data. Some potential problems could hide behind this apparent prosperity, especially with regard to quality. Construction quality is one of the most overlooked aspects of construction projects (Guandian, 2013).

#### **2.2.2.2 Recognising a construction quality crisis**

With the economic policy change on construction industry made by the Chinese government in 2013 to adjust the mode of economic development, economic growth has slowed down (Souhu, 2013). A slowdown in the construction industry accompanies the slower Chinese economic growth (Ernst and Young, 2016). Additionally, China's real estate investment growth slowed sharply from 9.9% in 2014 to 2.8% in 2015 (ibid.). The Chinese construction industry has lost some of its attraction, especially for companies without innovative technology and efficient management. Competitions between construction companies have increased, and their profits have declined further (LianheRatings, 2017). Not all companies can survive in this new wave of the depressed construction industry. No doubt, some of this is due to the shrinking profits in the construction industry, but some of it must be due to extensive management, manual operation, and low-technology in the Chinese

construction industry (Li, 2016). Chinese construction companies have to increase their competitiveness to face the challenge of reduced orders. Increasing competitiveness is not only about reducing the cost and time of projects but also about improving quality (European Commission, 1997).

Quality problems have always existed in the global construction industry which have been complained about poor quality performance (Hoonakker, Carayon and Loushine, 2010; Jamaludin, Mohammad and Variance, 2014; Yung and Yip, 2010; Oglesby, Parker and Howell, 1989; Loushine et al., 2006). Quality problem is a crucial issue for all nations, and China is no exception.

According to Chen and Luo (2014), about 822 construction incidents caused by low construction quality occurred in China in just 2006. As reported by Kam and Tang (1998), Hong Kong construction has also suffered from poor quality and dissatisfied customers. According to research on construction projects in Hong Kong, quality defects have directly cost the industry 3.5% of construction turnover in rework alone (He, 2014). The indirect costs account for 1.7% of the construction turnover, and 10% of project schedules are delayed due to rework (ibid). The frequently occurring incidents related to construction quality compel researchers to re-examine and reflect on building quality (Ma, Mao, Liu and Xi, 2014). The quality issue has been ignored by companies in the past, but now it is beginning to be recognised as a major problem to solve.

The quality problem seems to be common in the construction industries of other countries (Guan and Li, 2011). Chen and Luo (2013) state that the average global building quality is poor and report that substandard quality performance causes almost 29% of construction accidents in Germany. Poor building quality is also regarded as one of the most important problems in Malaysia (Jamaludin, Mohammad and Variance, 2014). As Sowards (2013) reports that rework which is caused by defects on construction site accounts the total reworks as high as 40%. The companies lost much money on defect reworks which are supposed to be avoided. It will cost more to correct defects if they are not detected through inspection and deliver to customers (Crosby,

1979). The defect rework will also delay the construction delivery time. Therefore, it is a barrier for contractors to meet customers' requirements (Sowards, 2013).

Comparing with other countries, the Chinese construction quality problems seem worse (Wang, 2013), which can be proved by the situation of housing quality in China. As Baoxing Chou, the vice minister of the China Ministry of Housing and Urban-Rural Development (MOHURD), mentioned in the sixth international conference on green and energy-efficient building in 2010, China has the highest rate of annual new-home construction in the world, but some of these homes could only have a 25 to 30-year lifetime due to quality issues (Ifeng, 2010). The data on high new built rate sounds impressive, but it generally means that the government has to demolish buildings for quality issues although they have only been built for 30 years. In contrast, the lifetimes of buildings in other developed countries (such as the UK, the United States and Japan) are far longer than in China. The average lifetime of Japanese buildings is 50 years, and in the United States, it could be 74 years; the UK has the longest building lifetime, which is almost 132 years (Ifeng, 2010). The comparison between China and other countries is damning. Additionally, according to the result of research on the quality of Chinese houses, 93% of respondents felt that their houses had quality problems and 46% of respondents even mentioned that quality problems affected their daily lives (Xinhua, 2013). Therefore, construction quality has attracted the attention of the Chinese government in recent years (Ministry of Housing and Urban-Rural Development, 2010).

### **2.2.2.3 Evolution of Chinese construction quality management**

In order to meet quality requirements by China MOHURD, the Chinese construction quality management has experienced several phases (Li, Anderson and Harrison, 2003). The Chinese government first followed the example of the Soviet Union's quality management after the Chinese Communist Revolution in 1949, which was mainly based on inspections (ibid.). Mathematical statistics were gradually used in construction quality management in some Chinese construction enterprises after 1958 (Zhang, 2008). The Chinese reform and opening-up policy in 1978 brought much foreign investment. Some new quality management theories were also introduced to

China (Zhang, 1999). The success of the total quality management (TQM) method in Japan encouraged the Chinese government to apply TQM to Chinese construction industries (Zeng et al., 2003). The Chinese government issued a construction law named ‘Interim measures for the comprehensive quality management of industrial enterprises’, which significantly supported TQM application in China (Shen and Chen, 2015). Since 1995, the Chinese government has adopted the GB/T19000—ISO9000 series of standards for the construction industry, which represents efficient modern management (Ou, 2012).

According to the result of the literature review, current Chinese construction quality is not good enough. The pressures of achieving competitive and satisfying customer and government’s requirements have pushed construction industry to regard quality as the first consideration. It is also known that construction quality is not only important in China, but also any other countries. It is a world’s attention topic. Conventional construction quality improvement approach should be challenged due to Chinese construction quality have not improved after many years.

### **2.2.3 The current Chinese construction quality improvement requirements**

In this section, the further study on current Chinese construction quality improvement requirements are conducted through reviewing current literature. As Table 2 illustrates, there are eight quality improvement requirements in China through analysing the literature review results. These construction quality improvement requirements are the foundation for further research.

Table 2: The Requirements of Current Construction Quality Improving Summarised from the Existing Literature

No.	Construction quality improvement requirements
1	Prevention mentality
2	Long-term consideration of quality-oriented mindset change
3	Win-win cooperation
4	Continuous improvement of standardization
5	Collaborative plans
6	Prioritising customer requirements
7	Continuous information requirements

**(1) Prevention mentality**

Wang (2012) describes the conventional Chinese construction quality management process as mainly conducted through random sample inspections of each sub-task. Although this inspection-based construction quality management could find some defects, its continuous reliability is doubtful (ibid.). The defects cannot be completely removed from the construction process as inspection-based quality control does not focus on the source of the defects (Li and Yang, 2013; Ge, 2011). Therefore, the same defect could happen again, and this situation could repeat many times (Cui, 2016). Han and Wang (2015) further confirm this situation. Moreover, various quality inspection processes require much of the workforce, materials and financial resources (ibid.). Excessive inspections would take much time which could also influence project schedules (Ge, 2011).

Proactive prevention of quality defects should be the priority of quality management by reviewing current Chinese quality management limitations. As the literature review result, the continuous reliability of inspection-based conventional quality management is challenged (Wang, 2012). Additionally, the quality defects cannot be completely removed through inspection-based quality management (Li and Yang, 2013). Therefore, further, improvement is required in the future development of construction quality management. Compared with the inspection of quality defects, proactive prevention has more advantages. Proactive prevention focuses on detecting the source of the defect and prevent it from happening (Han and Wang, 2015). The construction process is an emphasis on proactive prevention which tries to conduct a perfect process to prevent defects rather than only identify defects that have already happened (Zhai, 2015). High-quality construction can be ensured from the beginning of a project by adopting appropriate management (Li, Li and Liu, 2009). Hence, the prevention mentality should be advocated in the Chinese construction project.

**(2) Long-term consideration of quality-oriented mindset change**

The reason for construction defects occur so frequently may partly due to the industry

acceptance or acquiescence of quality failure (Oakland and Marosszeky, 2017). Setting a bottom line for quality defects is common for site managers (Sowards, 2014). A quality-oriented mindset should be the first consideration for implementing good quality management alongside various quality management principles and tools (Wen, 2000). In other industries, such as aeroplane or ship manufacturing, it is uncommon to accept quality defects. On the contrary, the construction site managers tolerate certain quality defects and accept the quality management approach to detecting and fix (Wen, 2000). This detection process can repeat over and over again, and the same defects may occur many times in one project (Wang, 2012). However, the quality defects lurking beneath the surface are seldom sought out (Shen and Chen, 2015).

As the result of analysing literature review results, changing to a quality-oriented mindset should be adopted as the main principle in future Chinese construction quality management. The construction quality change should be considered in a long-term perspective. Quality management in the future should encourage participants to correct their attitudes towards quality (Chen and Luo, 2010). No allowance for quality defects should be made in quality management and no compromise with quality defects (ibid.). The participants who are involved in projects are responsible for ensuring zero defects and conducting first-time quality (Pan, 2017). This kind of quality-oriented mindset requires patience and persistence (Zhang, 2017).

### **(3) Win-win cooperation**

From the results of Shen and Chen's research (2015), the participants usually tried to shift the responsibility of quality defects in the conventional construction process by blaming others' faults. Furthermore, contractors were blamed the most for poor-quality construction projects, which can be unjust (Zhang, 2008). Construction quality is achieved through cooperation between all participants, and it should not only be the concern of contractors (ibid.). The lack of a collaborative environment is one of the limitations of conventional construction quality improvement approaches.

According to the review of current Chinese quality management limitations, cooperation should be one of the most important characteristics of the future quality

management mode. Due to a large number of participants being involved in increasingly complex construction structures in modern projects, it is inevitable that cooperation is adopted to achieve construction quality (Liu, 2015). An effective way for participants to improve the overall construction quality is to meet and share their opinions with each other through win-win cooperation (Yang, 2009). In particular, cooperation between designers and contractors is needed as the quality of the design results is rarely transferred into construction quality (He, 2017).

#### **(4) Continuous improvement of standardisation**

Lacking standardised operational management is one of the problems in conventional construction quality management (Misfelde and Bonke, 2004). The standards of work are either abstract, or various standards existing at the same time (Li and Yang, 2013). Furthermore, the workers' specialisation degree is relatively low in the Chinese construction industry, with most of them lacking professional training. However, Construction tasks are usually processed by workers' experience, not on the basis of standards, which easily causes quality defects (Ou, 2012).

Continuously improving standardisation can be summarised as a requirement for the future quality management mode by reviewing existing research and its importance could also be identified through reviewing Chinese current construction quality management limitations. The difficulties on maintaining the standardisation of construction work are due to two reasons, which are lacking specific unified working standards and lacking professional workers to conduct construction work on the basis of work standards (Li and Yang, 2013; Ou, 2012). Therefore, more practical and less abstract standardisation is required due to the specialisation degree of Chinese construction workers. Experience-based construction should be replaced by standardised construction (Zhou, 2004).

#### **(5) Collaborative plans**

The quality of construction plan management is doubted for its poor performance (AlSehaimi, 2011). According to Marosszeky et al. (2002), the execution of tasks rarely follows the plan and less than 70% of planned tasks are completed at the end of

each week. A plan is only used to decide when works begin, without concern for the real conditions of the work site. The construction plan in Chinese conventional construction quality management is also not efficient (Zhao and You, 2015). The complex construction environment often leads to construction results that planners do not want (Yang, Xu and Tao, 2013). Furthermore, there is no continuous updating process of the plan. A top-down approach is used to make plans at the beginning of a project which is based on the assumption of the construction process is stable and constant progress, and the construction plan seldom changes during the whole construction process (Zhao and You, 2015). Unfortunately, this assumption can be wrong, as confirmed by many project application experiences in existing literature (Han and Wang, 2015).

According to the results of the literature review, conventional construction plans need to be changed. Top-down construction plans are not able to meet current construction requirements (Zhao and You, 2015; Han and Wang, 2015). The plan created before real construction begins which based on stable assumptions cannot always follow the on-site changes of real construction (Han and Wang, 2015). Therefore, the construction plan needs to be updated timely according to collected real site information, and all on-site participants' opinions are required to be considered in the plan due to they are familiar with construction status. As the result of reviewing existing literature, the collaborative plan approach is required to provide timely information and collect all on-site participants' opinions (Li, 2015).

#### **(6) Prioritising customer requirements**

Ge (2012) states that setting construction quality goals correctly is overlooked in conventional construction quality management. In conventional Chinese construction management mode, construction quality goals are mainly set based on national construction standards, technical specifications and quality requirements from customers before construction begin (ibid.). However, in many Chinese construction managers, the goal of construction quality is only through national standards and fulfil the quality requirements on the contract which overlook the continuing requirements from customers (Jiang, 2015). Thus, this kind of quality goal ignores satisfying the



continuous quality improvement requirements of the customer and can reduce customers' satisfaction.

Quality management modes based on customer requirements should be one of the directions of future modes. The quality standards should be set by customers, and not by designers or contractors (Gao, 2013). Quality goals should also not only conform to national construction laws or technical specifications but also to customer requirements, which are important in defining quality (Nie, 2016). Therefore, prioritising customer requirements are required in Chinese construction quality improvement.

### **(7) Continuous information requirements**

Site information is difficult to collect through the conventional method, and it is also easily ignored by site managers due to the complex construction site, unsmooth information entry and transmission, and paper-based information storage (Wang, 2012). The collecting, transferring and storing site information is also a big problem in conventional quality management (Wang, 2013).

The future requirements with regard to the continuous improvements of information are based on the good management of site information, including collecting, transferring and storing processes. A good-quality management system is always backed up by exhaustive information. However, conventional information management lacks efficient tools, which causes inaccurate site information collection, irregular information transformation and inefficient information storage. Continuous information support is required in the current construction industry (He and Li, 2013).

### **(8) Motivation management**

As Atkinson (1964) states, motivations and attitudes are the leading causes of quality failure, rather than technical issues. The softer aspects of management like motivation and attitude managements have drawn researchers' attention. Conventional construction quality management is mainly focused on the management of techniques rather than the management of people (Marosszeky et al., 2017). Motivation

management is ignored in Chinese conventional quality management in most cases, which results in a situation that the positive culture of quality cannot be created (Jiang, 2005). Workers' enthusiasm for executing standard work is difficult to maintain, let alone the workers' self-conscious and habitual attention to high construction quality (Ou, 2012).

Focusing on motivation management should be one of the characteristics of future Chinese quality management. According to the literature review results, the workers' enthusiasm, self-conscious and habitual attention are essential for achieving a high-quality project. Improving employees' motivations and attitudes towards quality is the main task of motivation management (Yang, 2017). Cultivating workers' consciousness of self-quality and a quality culture should be a priority of managers (Yang, 2017). Therefore, motivation management as a softer aspect of management should be focused on improving construction quality.

## **2.3 Historical Review of Lean Construction Ideology**

### **2.3.1 The emergence and development of lean construction**

Great success was achieved by Toyota Motor Corporation in the automobile industry in the 1950s, and this success caught researchers' interest (Takeuchi, Osono and Shimizu, 2008). Toyota's success was due to its management. This new management method was named the TPS. By the 1990s, this kind of management had gradually formed a new kind of management thinking - lean thinking (Hines, Holweg and Rich, 2004). Lean thinking began with a best-selling book named *The Machine That Changed the World*, which was published in 1990 (Mascitelli, 2004). Womack, Jones and Roos (1990) compare the lean production system and the traditional mass production system in their book, demonstrating the significant differences between the two systems (the comparison is shown in Table 3). The way that manufacturing management was implemented for a hundred years was challenged by the book. Continuous research was conducted by Womack and Jones (1996), and they defined lean thinking as a generic term. Lean thinking involves added value, continuous improvements, flattened organisational structures, the elimination of waste, teamwork, the efficient use of resources and cooperative supply chain management (ibid). The

publishing of *Lean Thinking: Banish Waste and Create Wealth in Your Corporation* brought the concept to maturity. This book follows a previous successful book by Womack, Jones and Roos (1990). Both books address the revolution of TPS in manufacturing. Lean production is a kind of advanced method of production management which can improve product quality, increase production productivity and reduce product costs (Modi and Thakkar, 2014). Toyota used lean production to break up the quasi-monopolistic position of America's mass production-based automobile industry and to establish a leading status in the world's automobile industry (Frigant, 2011).

Table 3: Comparison Between Mass Production and Lean Production (Womack, Jones and Roos, 1990)

	<b>Mass production</b>	<b>Lean production</b>
Basis	• Henry Ford	• Toyota
People-design	• Narrowly skilled professionals	• Teams of multi-skilled workers at all levels in the organisation
People-production	• Unskilled or semi-skilled workers	• Teams of multi-skilled workers at all levels in the organisation
Equipment	• Expensive, single-purpose machines	• Manual and automated systems which can produce large volumes with large product variety
Production methods	• Make high volumes of standardised products	• Make products which the customer has ordered
Organisational philosophy	• Hierarchical-management take responsibility	• Value streams using appropriate levels of empowerment-pushing responsibility further down the organisation
Philosophy	• Aim for 'good enough.'	• Aim for perfection

Compared with the production industry, the construction industry usually suffers from more quality defects and lower productivity (He, 2017). Therefore, research on how to apply lean production to the construction industry stands out among various studies on lean thinking. Due to the different characteristics of the production industry and the construction industry, lean production cannot be transferred to the construction industry without adaptive changes being made. The characteristics of the construction, such as large-scale, labour-intensive projects and transient, complex outcomes, should

be considered in lean production thinking (CIB, 2002; Deng, 2014). Koskela (1992) has introduced research entitled ‘Application of New Production Philosophy to Construction’ through Stanford University. This research aims to absorb core management concepts from the field of manufacturing to construction. Construction is understood as one kind of production in Koskela’s research. The concept of lean construction was proposed by Koskela through the International Group of Lean Construction at a conference in 1993. After that, the last planner system (LPS), as the main tool of lean construction, has been introduced by Ballard (2000), which has greatly improved construction schedules and control. The International Group of Lean Construction (IGLC) and the Lean Construction Institute (LCI), as two leading lean construction research institutions, have been set up since lean construction was first introduced. Today, an increasing number of studies focus on this research area (Tan, Xia and Yang, 2014). Lean construction theories are being improved, which could fulfil current construction requirements.

Although lean construction is a profit driver in many Western countries, the application of lean construction has just started in China (Tan, Xia and Yang, 2014). As China joined in the World Trade Organization (WTO), construction companies in China gradually realised that disparities and deficiencies existed in their project management levels in terms of high standards management (Building municipal commission of housing and urban-rural development, 2011). The internal features of Chinese construction companies, like poor construction management skills, a lack of efficient planning and control, insufficient coordination between departments, unbalanced resource allocation and a serious waste of construction resources mean that projects are usually rushed, the quality is often compromised and building flaws may become apparent when Chinese construction companies are under pressure to deliver (Zhang, Chen and Hu, 2011; Ma et al., 2014; Bristow, 2007). These issues encourage Chinese companies to transfer from extensive management to lean construction (Shang and Pheng, 2014). Some state-owned construction companies such as Construction and civil engineering companies of China and Beijing Construction Engineering Group have already adopted lean construction in their projects successfully, which can be regarded as a great step forward for Chinese construction management.

Lean construction is derived from lean production, while lean production is based on the TPS, which was very successful in the 1950s (Takeuchi, Osono and Shimizu, 2008). Lean construction is not simply adopting lean production theories in the construction industry. Lean production was originally used in the manufacturing industry. Lean production cannot be applied to the construction industry without adaptive changes being made due to the different characteristics of the manufacturing industry and the construction industry. Different researchers such as Koskela and Ballard have made contributions to the development of lean construction, which is a continuous process. Therefore, it can be predicted that the current lean construction theories and techniques may not be the final forms of lean construction. These current theories and techniques may be updated. New lean construction theories and techniques should be developed as needed. Moreover, the development status of lean construction in China is reviewed among existing literature. It could be concluded that the Chinese construction industry is open to using lean construction to solve some particular issues, such as cost management, schedule management and quality management.

### **2.3.2 Definition and principles of lean construction**

#### **2.3.2.1 Understanding lean construction**

After many years of development, different understandings of lean construction have become apparent. Different researchers with different perspectives define lean construction in different ways. Lean construction is understood by Dickmann et al. (2004) as a continuous process of meeting or exceeding the needs of all customers, eliminating waste and pursuing value. According to Koskela, Huovila and Leinonen (2002), lean construction can be defined as a way to minimise waste and generate maximum value. Lim (2008) states that lean construction is a way of balancing human resources, materials and other resources. He explains that lean construction helps to reduce costs and eliminate waste and allows projects to be delivered on time. Bertelsen (2004) understands lean construction in a different way: 'lean construction is a big scale of adaptation from the Japanese manufacturing principles, and the concept is implemented in the construction process'. Lukowski (2010) defines lean construction in a similar way: 'lean construction is the practical application of lean manufacturing

principles, or lean thinking, to the building environment'. As lean construction has begun to be researched in China, many Chinese researchers have also given their definitions of the concept. As He (2014) mentions, lean construction is defined as an integrated method to combine production management theories, construction management theories and the characteristics of the construction industry. Moreover, lean construction is also a management system which aims to continue to reduce waste and fulfil customers' requirements. According to Jiang (2005), lean construction is a new kind of management mode, and it is guided by lean thinking. Lean tools can be adopted to change the whole construction process. Eliminating waste, improving the production quality of construction and providing value to the customer are the main purposes of lean construction. There are many other definitions of lean construction which all cannot be listed. Although different researchers have given their definitions, the core content of the definitions is similar.

It could be summarised that the definitions discussed below describe lean construction in two different ways. The Lim's definition (Lim, 2008) can be regarded as an extension of Koskela, Huovila and Leinonen's definition (Koskela, Huovila and Leinonen, 2002). Balancing resources, reducing costs and delivering projects on time are included in the process of creating maximum value. The definitions from Lim and Koskela, Huovila and Leinonen are similar as they define lean construction from a functional perspective. In contrast, Bertelsen (2004) and Lukowski (2010) describe lean construction from the perspectives of source and development. Chinese researchers' definitions (He, 2014; Jiang, 2005) are similar to the first definitions given by Western researchers. Trying to reduce waste and providing the customers with value are two common aspects mentioned in the definitions. Therefore, lean construction can be described as a continuous process to eliminate waste and deliver value to the customer. The purpose of lean construction satisfies the customers' requirements.

#### **2.3.2.2 Basic principles of lean construction**

Lean construction theories are derived from lean production thinking and begin with three views of construction management: transformation, flow and value generation. The core objectives of all lean construction theories are eliminating waste and pursuing

perfection.

### **(1) The theory of TFF**

Koskela (1992) first combined lean production thinking with the construction industry and discussed three views of lean construction, which are called TFF views. TFF is the abbreviation of transformation, flow and value generation. This theory has become one of the foundations of lean construction (Gao and Low, 2014; Koskela, Huovila and Leinonen, 2002).

According to Koskela et al. (2002), the transformation view held a dominant position in the construction industry in the last century. Transferring input to output is the basic theory of the transformation view. In this environment, contractors are mainly focused on output, which is also called the result (Koskela, 2004). During the transformation phase, the overall project structure is broken down into smaller processes, called tasks (Koskela et al., 2002). Each manager is responsible for a task. Freire and Alarco (2002) describe the transformation view as a kind of management method, and it is helpful in improving productivity. Task management is the main application of the transformation view (Koskela et al., 2002). However, this view is not helpful for reducing waste (ibid.), and the clients' requirements may be ignored during the transformation phase (Huovila, Koskela and Lautanala, 1997).

The flow view is based on industrial engineering, and it was first described in 1922 by Gilbreth and Gilbreth (Koskela et al., 2002). The flow view was not mentioned in lean theory until Krafcik presented his work on Toyota's manufacturing practices (Koskela et al., 2002). The flow view is about the flow of raw materials and information through the construction process. Nothing is produced upstream until the customer requests from downstream. The downstream requirements decide the upstream actions. This view is advantageous to continually provide valuable outcomes.

The third view of TFF is the value generation. The major purpose of applying this view is to provide the best possible value to the clients (Koskela et al., 2002). Clients define the value of a project, which means that efforts have no meaning until they meet

the clients' requirements (Womack and Jones, 2003). The first important consideration in the value generation view is to understand the clients' requirements and views. Then, managers should try to fulfil clients' requirements as much as possible (Ballard and Koskela, 1998). This process is called value management. The whole theory of TFFV is listed below (see Table 4). According to Table 4, these theories interpret the lean construction process from three different aspects.

Table 4: The Theory of TFFV (Koskela et al., 2002)

	<b>Transformation view</b>	<b>Flow view</b>	<b>Value generation view</b>
Conceptualisation of production	As a transformation of inputs into outputs	As a flow of material composed of transformation, inspection, moving and waiting	As a process where the value for the customer is created through the fulfilment of his/her requirements
Main principle	Getting production realised efficiently	Elimination of waste (non-value-adding activities)	Elimination of value loss (achieved value in relation to the best possible value)
Methods and practices	Work breakdown structure, MRP, organisational responsibility chart	Continuous flow, pull production control, continuous improvement	Methods for requirement capture, quality function deployment
Practical contribution	Taking care of what has to be done	Making sure that unnecessary things are done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name of the practical application of the view	Task management	Flow management	Value management

## (2) Identifying waste

Eliminating waste is one of the main objectives of lean construction. Therefore, identifying waste is necessary. There are seven types of recognised waste in Koskela's research (listed in Table 5). These seven types of waste in the construction industry are



quality costs, external quality costs, a lack of constructability, poor materials management, the excess consumption of materials on-site, the working time used for non-value adding activities on-site and a lack of safety. Among them, quality costs produce the largest amount of waste in a project in the USA, taking up 12% of the total project costs. Therefore, improving construction quality is a priority in the implementation of lean construction (Koskela, 1992).

Table 5: Waste in the Construction Industry (Koskela, 1992)

Waste	Cost	Country
Quality costs (non-conformance)	12% of total project costs	USA
External quality cost (during facility use)	4% of total project costs	Sweden
Lack of constructability	6-10% of total project cost	USA
Poor materials management	10-12% of labor costs	USA
Excess consumption of materials on site	10% on average	Sweden
Working time used for non-value adding activities on site	Appr. 2/3 of total time	USA
Lack of safety	6% of total project costs	USA

### **(3) Identifying the value of construction projects**

Value is the basis of lean construction. This is not an economic concept, like the value of money (Ballard and Howell, 2004). The value in the context of construction should be understood as a production concept which is defined by the end customer (Womack and Jones, 1996). Construction activity is a value-added activity if it produces construction results in a way that is acceptable to the customer and they are willing to pay for it (Jiang, 2005). For example, quality inspection itself does not add value, but it can be regarded as an assurance measure to ensure that right value is delivered to the customer. Therefore, it is still valuable, but not to over-reliance, which will be explained in detail later.

### **(4) Mapping the value stream of construction projects**

According to Womack and Jones (1996), the value stream is defined as ‘series of processes which include problem-solving, information management and transformation tasks to deliver value to the customer’. All construction activities which can create value should be executed in order. The concept of the value stream can be

used as a tool to detect and eliminate waste. The key purpose of the value stream is to assess process value based on the customers' requirements (O'Connor and Swain, 2013).

#### **(5) Creating construction value flow**

Once the requirements of the customers have been accurately determined, managers can fully develop a particular map of the construction product value stream and eliminate the processes that do not create value. Materials, manpower, equipment and information are the fundamental elements of lean construction (He, 2014). The process of transforming these elements into valuable construction products without defects, stoppages and repetition are described as flow (Srichuachom, 2015). Value flow is the bridge that connects the entire project as a whole. The current management focus is on the performance of each task and not on the performance of a project (Ballard and Howell, 2004). However, each task can provide value, which does not mean that their combination can provide the greatest value. Therefore, the value of the whole project should be seen in the context of a whole project through a broad insight rather than be considered as a combination of each task value. Furthermore, the application of flow can managers find problems in the value stream.

#### **(6) The pull system based on customers' requirements**

The pull system is an important part of lean construction thinking. Construction task is part of this system that is based on the customers' requirements. Conventional construction is conducted with a push system, which pushes the construction product to the customers and does not consider the customers' requirements (Jiang, 2005). The pull principle involves conducting construction based on the customers' requirements. Additionally, as mentioned above, in adjacent construction stages, the workers of the subsequent construction stage are the customers of the workers of the previous construction stage. The previous construction results should be finished based on the requirements of the workers of the next construction stage (Misfeldt and Bonke, 2004).

#### **(7) Continuous improvements and seeking perfection**

Lean construction is not a static system, and it requires continuous efforts for

improvements to be made especially on the quality aspect. As Bicheno and Holweg (2009) state, unnecessary costs and unreliable services are caused by quality defects. Quality defects are an important factor that influences construction results. An outcome with zero defects is the ultimate goal of lean construction (Crosby, 1979). Lean construction managers are required to constantly analyse processes to eliminate quality defects and unnecessary costs and to reduce the time spent on tasks. As a result, defect-free construction results can be provided to the customer.

### **2.3.3 The potential use of lean construction to improve construction quality**

#### **2.3.3.1 The necessity of implementing lean construction to improve Chinese construction quality**

The necessity of adopting lean construction to improve construction quality management has been affirmed by many researchers in existing literature. Ballard and Howell (2008) reveal that the current project management is chaotic and almost 54% of the promised work is not completed per week in the construction industry. The limitations of conventional management are apparent. Moreover, it is advised by Howell (2008) that lean construction is adopted to reduce the wasting of time and costs without sacrificing quality.

Lean construction is regarded as an efficient way to eliminate waste (including quality defects) and increase profits (Salem et al., 2005). With profit margins declining in the construction industry (Ernst and Young, 2016), construction quality has become a way to increase the competitiveness of construction companies in China (Zhang, 2007). It means that lean construction could be a useful tool to achieve competitiveness in the construction industry.

According to the results of the literature review, many Chinese researchers also identify the necessity of applying lean construction in construction quality management. The benefits of applying lean construction in China can be seen for two reasons: efficiently reducing the waste resulting from quality defects and increasing quality-based competitiveness. Wang (2012) indicates that lean construction is useful in identifying the actions that do not provide value and eliminating waste. Construction

quality is achieved through lean construction-based quality management without extra expense in terms of cost and schedule. Furthermore, lean construction can efficiently enhance the trusting cooperation between participants and achieve construction quality through efficient information sharing and communication (ibid.). With Chinese construction companies gradually entering the international construction market since 2001, these companies are facing more and more pressure with regard to competition (Building municipal commission of housing and urban-rural development, 2011). A gap between well-known international construction companies and Chinese construction companies still exists (Ou, 2012). New approaches are needed to increase the quality-based competitiveness of Chinese construction companies. Lean construction could be a direction to take in the development of the Chinese construction industry (Shen and Chen, 2015).

#### **2.3.3.2 Reviewing construction quality improvement approaches based on lean construction**

According to the research results of Alves and Tsao (2007), only 0.7% of studies on lean construction published between 2000 and 2006 focused on lean construction and construction quality, accounting for a very small proportion. Construction quality improvement research is often ignored in comparison to other research areas.

In Misfeld and Bonke's research (2004), the guidelines of a quality control system which attempts to integrate lean construction are given. The innovation in their research is reconstructing the responsibilities of workers and managers in terms of quality. Site workers are encouraged to take responsibility for managing quality. Moreover, Han and Wang (2015) have built a lean construction quality management model. The four layers in this model are the support layer, the management layer and executive layers. Although there is a lack of further detailed information on this model, Han and Wang' research still provides a new approach to analysing the interactions between lean construction and construction quality improvement. Tawfik and Othman's (2013) aim is to identify the role of quality management in minimising project waste and discussing the relationships between quality management, waste minimisation and lean construction. Project waste minimisation requires the support

of quality management and the result of waste minimisation based on quality improvement could lead to lean construction. Some quality management tools which complement the LPS have been developed and trialled on a construction site by Marosszeky et al. (2002). This research helps to combine lean construction with construction quality improvement more efficiently. The research results of Marosszeky et al. can be divided into three aspects, which are workforce responsibility, process control and a recording system. This is one of the few studies in the field of lean construction tools. Liu and Shi (2017) introduce a KanBIM quality control system to improve construction quality. The kanban technique is a kind of lean construction technique that can be adopted to improve construction quality. The highlight of Liu and Shi's paper is using BIM as an auxiliary tool to support information collection and sharing. Li and Yang (2013) provide a quality evaluation model based on the lean construction philosophy. The highlight is that customer satisfaction based on lean thinking is involved in this model. Additionally, the visual management of lean construction is also considered helpful in improving construction quality (Greif, 1991; AlSehaimi, 2011). A book written by Oakland and Marosszeky (2017) provides guidelines for lean construction and quality management. This book can be regarded as an introductory book that provides a comprehensive background of lean construction. The relationships between lean construction and quality management are discussed in detail in the book.

Some theories related to lean construction also indicate the influence of lean construction on improving quality. Quality defects should be prevented, rather than detected through inspections (Crosby, 1979). 'Zero defects' should be the perpetual target for managers (Crosby, 1979) and quality improvement should always be pursued in lean construction (Chen and Luo, 2010). Furthermore, a quality-oriented culture which advocated in lean construction needs all participants to accept it for ensuring construction quality (Marosszeky et al., 2002).

Some indirect research also exists in lean construction and quality management. In these researches, the interaction between lean construction and construction quality management is implied. Although Srichuachom (2015) focuses on using lean thinking

to improve product quality in manufacturing industry in Thailand, the study can also indicate the interactions on principles between lean construction and construction quality improvement. AlSehaimi (2011) aims to improve the construction planning phase by using the LPS. As a result of his research, the reliability and the quality of the construction planning phase have increased which then indirectly influence the final construction product quality. The goal of concurrent engineering is to create an integrated design for projects to be achieved in a short time, at a low cost and with a high-quality design (Anumba et al., 2006). Due to design quality could indirectly influence the quality of plan and construction (Gao, 2013). Therefore, concurrent engineering has the potential to influence final construction product quality in the construction process. Yu (2010) places emphasis on providing a lean framework to help construction companies improve their efficiency. However, some lean techniques introduced in his research also presents the role of construction quality improvement such as standardised work. In some other articles, while there is no direct link between lean construction and quality, it is certain that it has a positive impact on quality, which has laid a foundation for further lean quality management research (Tezel and Aziz, 2015; Salem et al., 2005; Koskela, 1992; Ballard 2002).

According to the literature review result, the researches on integrating quality improvement and lean construction are still relatively rare. The relationship between lean construction and construction quality improvement are vague and fragmented. No common quality-based lean construction theories and techniques are widely recognised. This research seeks to explore the links between lean construction and construction quality improvement to fill this gap. It was clear that lean construction was a kind of philosophy, which provided a theoretical guide for improving construction quality. Moreover, some lean techniques were formed from lean theories to help to achieve lean quality goals. Therefore, the existed researches on quality-based lean construction should be categorised in two perspectives: theory aspect and technique aspect.

The potential quality-based lean construction theories and quality-based lean construction techniques identified from the literature review were the foundation of

developing interview template which related to lean construction and construction quality. Moreover, the final quality-based lean construction theories and quality-based techniques in interaction framework were concluded through literature review results and case study results.

### **1) Potential quality-based lean construction theories**

The potential quality-based lean construction theories summarised from the existing literature are listed in Table 6. A further detailed discussion of the literature review findings is summarised below.

Table 6: Potential Quality-based Lean Construction Theories Summarised from the Existing Literature

<b>No.</b>	<b>Potential quality-based lean construction theories</b>
1	Proactive quality defect prevention culture
2	Conversion to a quality-based mindset
3	Decentralised control-giving authority to workers
4	Customer quality requirements
5	Continuous quality improvement

#### **(1). Proactive quality defect prevention culture**

Prevention-based proactive quality management is one of the requirements in lean construction theory which is gradually being accepted in the current construction industry. As Crosby (1979) states, quality defects should be prevented in the process of construction rather than achieved by inspection in the final product. Inspection cannot result in high quality without waste but prevention can. By adopting appropriate management, high quality can be achieved during initial construction through built-in-quality approaches (ibid.). The cost and the time of remedial work could be reduced if all processes are completed correctly initially. Compared to proactive quality defect prevention approaches, inspection-based post-action quality control can only be used to detect defects which have already caused waste (Wen, 2000). Even if quality problems can sometimes be detected through inspections, some quality defects may be hidden because the inspections lack the support of all workers and the limitations of detection technology development (Wang, 2012). An overreliance on inspections to

ensure project quality can lead to workers thinking that quality is only related to their supervisors. Additionally, inspection itself neither adds value nor corrects the causes of quality defects (Marosszeky et al., 2002). Furthermore, once a quality defect is found in inspection-based post-action quality management, the defect has to be rectified or reworked. The project cost would then increase, and the schedule would be delayed due to this rectification and reworking. Therefore, a proactive quality defect prevention culture as a quality-based lean construction theory is the solution to improving construction quality. Establishing a proactive quality defect prevention culture helps to improve the current phenomenon of the overreliance on inspections.

## **(2). Conversion to a quality-based mindset**

According to past studies, quality defects are normally accepted in the construction industry, and it is common for site managers to set a bottom line for quality defects (Soward, 2013). This negative mindset can result in people spending a long time and huge costs on potentially useless activities. As Oakland and Marosszeky (2017) state, these useless activities can include ‘correcting errors, looking for things, finding out why things are late, checking suspect information, rectifying and reworking, apologising to customers for mistakes, poor quality and lateness’. However, lean construction pursues activities that are high-quality at the right time and without waste, and no quality defects are accepted (Crosby, 1979). According to Crosby’s “Zero Defects” theory, defects could be eliminated by using the appropriate management. “Zero Defects” is an attitude to prevention (Suarez, 1992). It brings workers’ subjective positivity to do things right at the first time. Quality is not relayed on detection and test. Any management culture that compromises with quality defects is bound to fail. An essential step when implementing lean construction to improve construction quality is to encourage a shift in the quality-based mindset. A quality-based mindset requires all participants to accept it, which includes workers and managers, who are then committed to creating value for the clients (Marosszeky et al., 2002). Workers do not need to be forced to ensure high-quality construction. They need to shift their mindsets and ensure quality on their own.



### **(3). Decentralised control- giving authority to workers**

Before discussing the decentralisation of control, it is necessary to investigate the relationship between inspection and quality. It is certain that the quality of construction products is gradually realised through the construction process, and not through external supervision and inspections (Wang, 2012). Excessive dependence on inspections is detrimental. However, even if inspections do not create value, it is still necessary to use inspections as an approach to ensure the final construction result. It is difficult to eliminate quality defect through prevention alone due to current technological constraints (Li, Li and Liu, 2009). Moreover, the occurrence of accidents also increases the uncertainty of quality. Inspection can be regarded as a supplement to high-quality prevention and a measure that ensures zero defects in construction products, which is undoubtedly valuable to the whole construction process (Zhai, 2015). Therefore, quality inspection in quality management should not be completely discarded, but attention should be paid to the problems of cost and schedule increases caused by quality inspections. The best way to implement quality inspections in the construction process is to simplify the quality inspection process as much as possible (Li, Li and Liu, 2009). Therefore, decentralised control, which involves giving authority to the workers, can be adopted to enhance the construction quality in a simple way. In general, although the theory of lean construction to improve construction quality is dependent on high-quality prevention, inspections can also be used to ensure the final project quality.

Any underlying financial costs of defects will increase based on the length of time taken to discover the defects (Pan, 2017). It is necessary to eliminate quality defects when they appear and to minimise the loss of quality if the defects cannot be completely eliminated in the high-quality prevention process. Quality managers should monitor the construction process as closely as possible to identify and correct quality defects (Zhu, Liu and Wang, 2007). It is obvious that construction workers are the employees closest to the construction process. Site workers are encouraged to take responsibilities to ensure construction quality (Misfeld and Bonke, 2004). Womack et al. (1990) mention that on-site workers are well-placed to control quality and correct defects. Therefore, in lean quality management, some quality inspection duties are

transferred from quality inspectors and on-site managers to construction workers (Wang, 2012). According to Misfeld and Bonke (2004), every worker is responsible for ensuring construction quality. After the completion of work, workers need to carry out relevant inspections of self-quality. The next stage of the work should only start after this inspection is completed. The workers in the next stage should first check the quality of the work completed in the previous stage. Repair work should be undertaken immediately if quality defects are detected. It is the best way to reduce the loss suffered from rework as the workers and the equipment of the current stage have not to leave current construction stage for waiting quality check result. The next stage of the construction work can begin only after the quality of work is completely confirmed (Misfeld and Bonke, 2004).

#### **(4). Customer quality requirements**

The construction process can be regarded as providing value based on the customers' requirements. All construction activities intend to increase the value of construction projects, reduce waste and create value streams (Zhu, Liu and Wang, 2007). The final goal of lean construction is to increase the customers' satisfaction, which includes their satisfaction with quality. Today, quality requirements are becoming more personalised and diversified and customer satisfaction with quality has become a dominant factor in determining the success or failure of a project (Li and Yang, 2013). Focusing on the customers' quality requirements as a theory of quality-based lean construction is related to the aim to conduct all construction activities based on the customers' quality requirements, and the goal of detecting customer quality requirements is to understand the real quality needs among various vague, uncertain and varying requirements from the customers. Additionally, the customers' requirements may change over time. Therefore, continuous efforts should be made to obtain the newest customer requirements (Oakland and Marosszeky, 2017).

#### **(5). Continuous quality improvement**

Although it is difficult to achieve perfect quality, the goal of perfect quality should be pursued perpetually. Perfection is the perpetual target in a project (Crosby, 1979) and continuous improvement is the key to improving lean construction quality (Chen and

Luo, 2010). In lean production, continuous improvement involves reanalysing the value stream of products and eliminating all kinds of waste (Ou, 2012). Similarly, quality-based lean construction also requires the continuous analysis and measurement of each influencing factor and the root cause of defects (Ge, 2011). Additionally, construction quality can be continuously improved by accumulating experience from analysing and learning about quality defects. Moreover, continuous quality improvement in lean quality management is not limited to improving the work process and workers' abilities; it also places emphasis on the continuous improvement of the quality awareness of the workers.

## **2) Potential quality-based lean construction techniques**

The quality-based lean construction techniques discussed below are not new techniques but are frequently used in lean construction. Some of these techniques are pillars of lean construction and support the application of lean construction. However, compared with other application direction, these techniques are rarely discussed from the perspective of quality. The quality functions of these techniques are still unknown. Reviews are conducted of existing literature, and the quality functions of these lean construction techniques are summarised (see Table 7).

Table 7: Potential Quality-based Lean Construction Techniques Summarised from the Existing Literature

<b>No.</b>	<b>Potential quality-based lean construction techniques</b>
1	Last planner system
2	Visual management
3	Kanban
4	Concurrent engineering

### **(1). Last planner system**

The LPS has been considered one of the most important techniques in lean construction since it was introduced by Ballard and Howell (Bertelsen, 2002). The LPS has been tested and refined for many years, and it brings many benefits to the construction industry (AlSehaimi, 2011). The LPS is a workflow control system which can empower front-line workers to make decisions about what work to commit to, as

well as improving workflow and measuring the variability of production systems (Abdelhamid, 2008). The LPS offers the promise of stabilising the workflow by eliminating the uncertainty in construction plans (Christoffersen, Sander and Bojsen, 2001; Jiang, 2005). The LPS also demonstrates its functions in the collaborative management of construction participants (Ballard, 2000). Today, the potential of the LPS is investigated with regard to the improvement of construction quality (Li and Han, 2008).

Conventional plans are mainly made by project managers through Gantt charts and the critical path method (Tarar and Dang, 2012). The tasks in construction plans are often assigned from the top down. This kind of plan is made based on the managers' experience and an assumption of stable construction conditions. Construction projects are often complex, and construction work conditions change constantly. Plans that are made according to the managers' experience, which lack the consideration of real-time on-site conditions, are unable to fulfil the current construction requirements. The longer the forecast of a plan, the more room for error. Moreover, the more detailed the forecast of a plan, the more wrong it can be (Han and Wang, 2015). Conventional plans lack the function to steer construction towards planned objectives proactively. As discussed in Section 2.3.3, through conventional plans, less than 70% of planned tasks are completed at the end of each week (Marosszeky et al., 2002). Under the guidance of such a plan, the bad quality results can be predicted.

The LPS overcomes many of the drawbacks of conventional construction plans. Construction quality improves with the increased quality of construction plans (Gao, 2013). In contrast to conventional plans, the obstacles that affect construction are considered and eliminated in the LPS based on timely onsite information, which increases the reliability of the construction process (Marosszeky et al., 2002). The significant difference between the LPS and conventional plans is that last planners (foremen) are involved in the planning phase. Last planners are invited as construction planners to offer advice. A bottom-up approach is involved in the plan-making phase. Last planners are more familiar with construction sites and have more awareness of on-site conditions than managers. Any changes in the construction conditions can be

perceived by last planners. A construction plan that incorporates last planners' opinions is relatively feasible under the actual construction conditions, and the quality of the construction work is expected to be guaranteed (Wang, 2012). Additionally, the last planner is the foreman, and they participate in the actual construction, which could avoid quality problems by the foreman paying attention to quality control priorities in advance (Yang, Gao and Xu, 2013). Under the LPS, construction workers no longer passively accept top-down plans, but they participate in the plan-making process, which enhances the rationality of the plan.

## **(2). Visual management**

The visual management of construction is similar to the visual management of lean production in which visual techniques are used to help with on-site management (AlSehaimi, 2011). One of the most important advantages of visual management is that it improves quality (Greif, 1991). The purpose of applying visual management is that to have a better understanding of standards and defects which are deviating from these standards can be recognised immediately (Koskela, 1992). According to Dave (2013), increased self-management, reduced waste, improved construction site transparency and reduced obstacles in information transformation are related to visual management. Moreover, as Tezel et al. (2011) state, visual management affects many aspects of construction, such as communication abilities, construction process transparency and workplace discipline.

Due to the characteristics of human observation, visual information is more memorable than written instructions (Intergraph, 2012). Visual management makes work processes easy to see. Work standards can be described in the form of pictures, and work processes can be demonstrated through flow charts (Dave, 2013). These visual standards and work processes are easily understood by workers, which improves the construction quality. Work plans and site layouts can be explained via communication boards (O'Connor and Swain, 2013). Communication and collaborative work are also improved through visual management (ibid.). Some physical models can also be used to guide on-site workers in construction operations. Therefore, visual management has a strong impact on construction quality in lean construction.

### **(3). Kanban**

Kanban is regarded as a step of the visual management process by some researchers. However, kanban has its own characteristics and should not be limited to visual management. Any selection of kanban classification is subject to debate (Yu, 2014). With regard to visual management, kanban is viewed as an independent technique in this research.

The kanban management technique is derived from Toyota production techniques in Japan. It provides strong technical support for just-in-time (JIT) production management in the manufacturing industry, and it is also one of the core technologies of lean production (Sugimori, 2007). Kanban presents a pull construction control philosophy, in which the current construction work is pulled by the requirements of the work in the next step. Kanban based on pull control is used to produce the construction product on demand at the required quality, in the right quantity and at the right time (Arbulu, Ballard and Harper, 2003). Kanban is not only a signal which contains instructions like information related to construction and material requirements, but it can also be an information communication board, which includes all of the quality, schedule and safety information every week, as well as changes in the plan (Liu and Shi, 2017). The integrated adoption of kanban, the LPS and visual management could increase the transparency of construction information and help construction plans be implemented more effectively.

### **(4). Concurrent engineering**

The term concurrent engineering (CE) was introduced in the late 1980s to describe a process in which designers work concurrently with producers (Huovila, Koskela and Lautanala, 1997). It is one of the main concepts of lean thinking. CE refers to a lean technique of collecting resources from each building phases in a project lifecycle, such as the construction stage, to improve the design efficiency and quality (Pena-Mora and Li, 2001). The goal of CE is to create an integrated design that can be achieved in a short time, at a low cost and high quality (Anumba et al., 2006). CE can also effectively reduce the rework needed in the construction process, which is usually the result of

design issues (Wang and Wang, 2006). CE also reduces the costs of projects and improves the construction quality by optimising the project design through fully integrating the views and experiences of all construction participants.

For maximising the effects of CE, all stakeholders should be involved from the beginning of a project, and a multifunctional team should be formed. This multifunctional team is responsible for the collaborative design and making early considerations of all life cycle issues for the project (Garza et al., 1994). The constructability of designs can be improved by contractors being involved in the design stage. Any design that could lead to construction quality defects would be rectified before construction began (Ou, 2012). This is a chain reaction. The contractors' participation in the design phase makes the design reasonable. Then, the construction plan would be more reasonable because the contractors have a good understanding of the drawings created during the design stage. The construction quality can be finally improved with reasonable designing and planning.

## **2.4 Historical Development and Current Researches of BIM**

### **2.4.1 Historical development of BIM**

BIM is an emerging construction technique that helps to design and construct buildings digitally. It has been gradually accepted as a potential solution to reduce inefficient construction and the wasting of financial resources (Infocomm, 2011). Digital design, construction simulation and facility management in BIM could help companies to improve their competitiveness (He, Wang and Ying, 2012).

BIM is a kind of parametric model which components in the model such as a set of walls could be parametrically adjusted with each other (Goubau, 2017). Tracing the history of BIM, it is necessary to go back to review the early days of parametric model development. The first computer-aided design (CAD) system which called 'Sketchpad' was developed in the USA in 1963. It began a way of displaying and recording geometry information in the computer (Cohn, 2010). More and more researches were proposed in the 70s and 80s to continuously develop a parametric model for a more intuitive and simple way of presenting information which included the prototype of

BIM. The concept of BIM was basically described in a paper published by Charles Eastman in the later 1970 s. The prototype of BIM contained a sortable database which information was categorised by attributes, graphical user interface, orthographic and perspective views (Goubau, 2017). Additionally, the continuous development of BIM boarded its application range from design phase to a whole construction life which contained pre-construction phase, construction phase and pose-construction phase (Latiffi et al., 2013).

Currently, a large number of construction companies have adopted BIM in the United States, and it is being promoted by the government (He and Li, 2013). According to the survey results of the SmartMarker Report (2012), the adoption of BIM in North America increased by 43% in the space of just six years from 2007-2012 (as Figure 1 shows). Additionally, in 2012, the percentage of companies using BIM reached 71% in North America (ibid.). The UK has also become one of the leading countries for BIM development (UKCO, 2011). The UK government encourages companies to use BIM, and it is playing a more and more important role in the UK construction industry (Cabinet Office, 2012). As the chief executive officer of HOK (A famous global design, architecture, engineering and planning firm), MacLeamy, mentions that the company now uses an ambitious and advanced UK-driven BIM programme (HM Government, 2012). Furthermore, BIM can enhance the international image of UK designers, contractors and product manufacturers, which means high-quality and practical on design and construction. BIM is a ‘game changer’, and it can advance the status of the UK construction industry among the global construction industry (HM Government, 2012). In Europe, the European Parliament approved a directive for public sector procurement which includes two references to BIM (BIM Task Group, 2013). These references encourage public authorities to consider using BIM for public works and to pay attention to the benefits that BIM offers to public construction projects (ibid.).



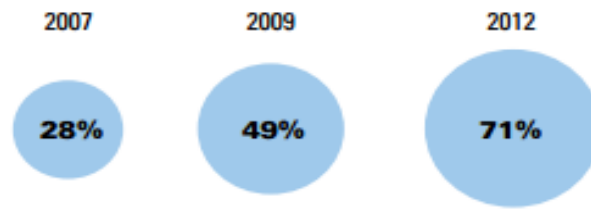


Figure 1: The percentages of companies in North America using BIM in 2007, 2009 and 2012 (SmartMarker Report, 2012)

Although BIM is popular across the world, the average application of BIM is still at a low level. As examples from the UK show, research results demonstrate that some constructors are not aware of the differences between BIM and CAD and believe that BIM and 3D CAD are synonymous (NBS, 2013). This situation has been improved since the UK government introduced its goal to achieve Level 2 BIM (fully collaborative 3D BIM). There are four levels of BIM application. They are Level 0 (2D CAD drafting only is utilised), Level 1 (a mixture of 3D CAD for concept work, and 2D for drafting of statutory approval documentation and production information), Level 2 (collaborative working and information change through a coordination process) and Level 3 (iBIM which creates international open data' standards, establishes a new contractual framework, creates a cooperative cultural environment and trains the public sector client to use BIM), which are shown in Figure 2. UK construction companies have made great progress on BIM development in these years. The results of a survey conducted in 2013 indicate that 47% of companies claimed that they had already reached Level 2 and some companies even claimed that they had arrived at Level 3 (NBS, 2013). According to NBS (2018) reported in 2018, BIM Level2 are generally achieved in government procurement in the UK and it also usually accepted in private sector procumbent.

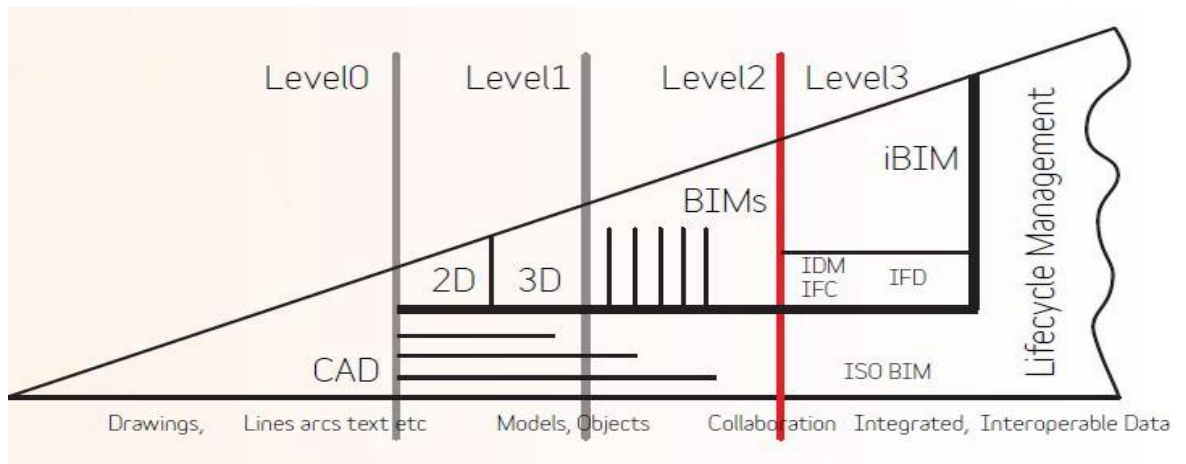


Figure 2: Levels of BIM (NBS, 2013)

BIM, as a new technology, has emerged in China in recent years. With the view that BIM has huge potential in the future, Chinese construction companies have focused on BIM and have begun to adopt the process to increase their competitiveness (Autodesk, 2007). Additionally, the Chinese government also advocate promoting the application of BIM in the Chinese construction industry. The MOHURD issued a government policy on Chinese construction develop named ‘Outline of development of construction industry informatisation (2001-2015)’ in 2011 and BIM was highlighted in this policy as goal and key of Chinese future construction industry development (Ministry of Housing and Urban-Rural Development, 2011). In China, BIM has been implemented successfully in many projects, such as the China Pavilion at the Shanghai Expo 2010 and the Shanghai Centre. In these projects, software like Autodesk Revit Architecture, Autodesk Revit Structure and ArchiCAD, were implemented in the design, construction and operation stages (He, Wang and Ying, 2012). One of the most successful regions in China in terms of the application of BIM is Hong Kong (ChinaBIM, 2013). Companies in Hong Kong have applied BIM to achieve clash detection, design visualisation and design evaluation for years (Wang, 2013). Although BIM has been applied in some projects and areas, the general level of BIM application in China is relatively low. According to data reported by the Chinese construction industry association (2013), in 2012, about 55% of construction companies know about BIM, but less than 15% of construction companies use BIM in their projects. However, according to the report in 2014, 67% of construction

companies in China claimed to start using BIM and over 10% of companies had used BIM in over 50% of their projects (Shanghai construction trade association and Luban consulting, 2014). In the past two years, the application of BIM had increased a lot. The rapidly increasing BIM adoption rate in China presents requirements and motivations of applying BIM are strong in China. Due to the development of BIM in China has just barely begun for several, in general, the level of BIM application in China is still in its initial stage (He, Wang and Ying, 2012).

## **2.4.2 Definition and advantages of BIM**

### **2.4.2.1 Understanding BIM**

BIM is the process of generating and managing building data during a project's life cycle (Tsai et al., 2010). There are many definitions of BIM. From a 3D parametric modelling perspective, BIM encompasses building geometry, spatial relationships, geographic information and the quantities and properties of building objects (He and Li, 2013). BIM acts as a set of interacting policies, processes and technologies that generates a methodology to manage the essential building design and project data in a digital format throughout the life cycle of a building (Penttilä, 2006). BIM may also be defined as a shared knowledge resource during the life cycle of a building, and it includes architectural design, construction and facility management (Eastman et al., 2011). BIM has been developing for over 15 years (ibid.). Today, it is known and accepted by more and more companies.

According to the research result of Latiffi, Brahim and Fathi (2013) which investigate the development of BIM notion from 1975 to 2013, BIM is mainly defined from six perspectives, which are design, estimation, construction process, building life cycle, performance and technology. Different terms on the definition of BIM have been used and expanded widely with different perspectives. However, according to Smith (2014), a definition of BIM which is proposed by the US National Building Information Model Standard (NBIMS-US) Project Committee is recognised across the globe construction industry. The BIM definition in NBIMS-US is described as (NBIMS-US, 2005):

Building Information Modeling (BIM) is a digital representation of physical

and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition

BIM should contain various kinds of project related information such as spatial relationships, geographic information, and quantities and properties of building objects, rather than just geometry information (Eastman, 2008). BIM should cover multi-dimensional information to realise its 3D (object model), 4D (time), 5D (cost), 6D (operation), 7D (sustainability), and 8D (safety) functions (Smith, 2014).

A number of misconceptions exist about BIM due to its complex and broad nature. For instance, 3D CAD generates simple visualisation, but there is no accurate parametric intelligence or information about the objects in the model (Li, 2016). This is not the real BIM. It is also important to understand that BIM is not only a technological platform or tool that is used by a small group of people in construction projects (He, Wang and Ying, 2012). It is the basis for new construction capabilities and it changes the role between construction stakeholders (Eastman et al., 2011). BIM also can guarantee high-quality construction if it is applied well.

BIM has many definitions, and these definitions are given for different purposes. However, these definitions all emphasise the importance of the information in BIM. The BIM is a 3D parametric model which includes building information such as building geometry, spatial relationships, geographic information and the quantities and properties of building objects (Li, 2016). The most accepted definition of BIM is given by NBIMS-US project committee. This research will also adopt this definition to understand BIM.

#### **2.4.2.2 The advantages of applying BIM**

BIM is parametric objective modeling which can use data to represent a ‘real-world’ (Sacks, Radosavljevic and Barak, 2010). As mentioned before, BIM can intuitive

display physical information like building geometry and spatial relationships and it also represents abstract simulations, such as clash checking and quantity calculation (ibid.). BIM can benefit in many areas for its multi-functional characteristics (Won and Lee, 2010). As Figure 3 illustrates, BIM benefits project from six aspects which allows project to have greater speed, lower cost, better coordination, more safety, easier maintenance and higher level of customisation.

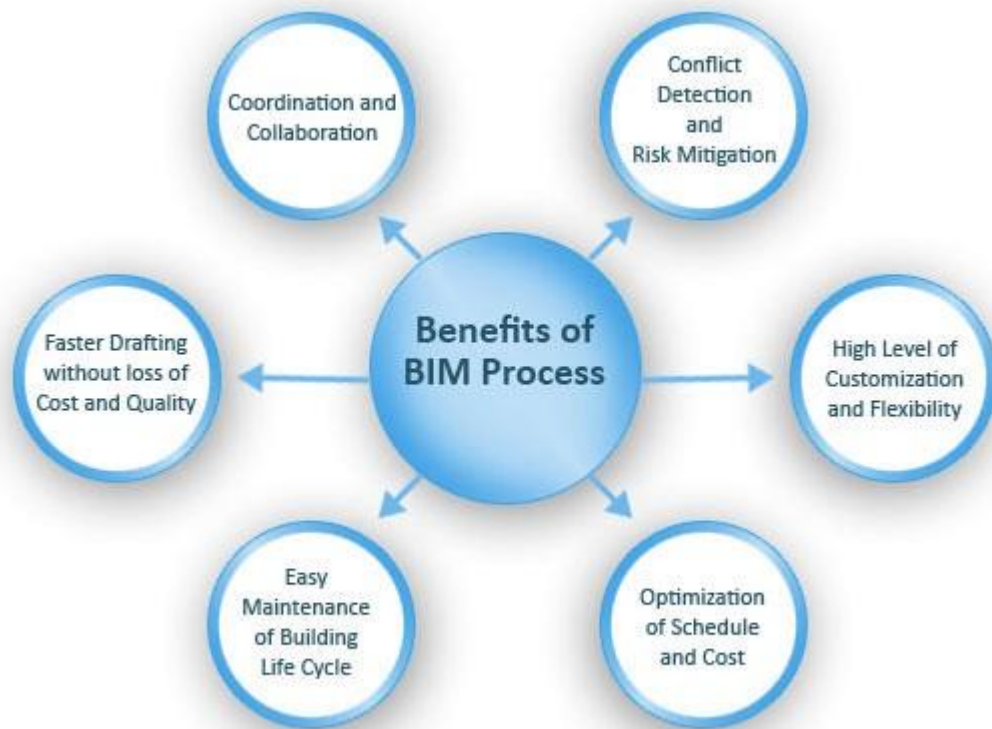


Figure 3: Benefits of BIM Process (IranBIM, 2017)

According to a whitepaper from Autodesk (2002), BIM not only benefits for faster delivery and lower cost, but also results in better quality work during the phase of design, construction, and operation. The quality of information is ensured by BIM and (He, Wang and Ying, 2012). For the mechanism of information management in BIM, regardless of how many times a design is changed and which stakeholder changes it, the data will remain consistent and accurate. The model can also be updated as the project proceeds, which also ensures information accuracy (ibid.). Due to 3D and 4D functions of BIM, virtual design and virtual construction are usually applied before

physical construction begins. During the virtual design stage, architects can build a virtual model in a 3D environment which provides an initiative view of design drawings. The combination of 3D presentation of building geometry information and spatial relationships and other information embedded in building objects, such as quantities and properties of building objects can detect design defects easier (Li, 2016). Additionally, 4D BIM which covers schedule information allows people to ‘build buildings twice’, which means that people can first construct a virtual construction on-screen and then build it physically on-site when the project begins. This process also benefits for delivery better quality.

### **2.4.3 The potential of a BIM driven approach for quality improvement**

#### **2.4.3.1 The necessity of adopting BIM to improve Chinese construction quality**

The most common computer-aided tool used in the Chinese construction industry is CAD, which has been used for more than 20 years (Last finance news, 2018). Although CAD and other computer-aided tools have developed during these 20 years, the shortages of cooperation, simulation, optimisation and parametric design limit these tools’ development in terms of construction quality improvement (Zou et al., 2013). The emergence of BIM could bring about a revolution in Chinese construction quality management.

To a large extent, the quality control in China is mainly based on detecting and modify defects by using supervisors’ own construction experience and 2D-based CAD drawing which means the insurance of high construction quality depends mainly on personnel quality (Zhang, 2017). Additionally, quality inspection plans are influenced by managers’ subjectivity, so objective and effective plans are hard to achieve (ibid.). BIM is one of the best ways to overcome subjective influences due to accurate and reliable data. Quality inspection plans and actual inspection process are supported by sufficient quality information and data in BIM (Pooyan, Griffis and Lawrence, 2009). Different plans can be simulated to select the best one through BIM. There is a strong need to find an efficient tool such as BIM to replace CAD in the Chinese construction industry (Zou et al., 2013).

The current quality management in China focuses on detecting quality defects through inspection rather than avoiding defects (Pan, 2017). Even if the defects can be modified, this may result in cost increases and time delays. BIM provides a chance to solve this problem. The mechanisms of BIM make the control of defects before they occur achievable. The quality of construction is ensured in the construction process rather than in final inspection (Achkar, 2016).

The current Chinese construction industry lacks efficient construction information transmission tools. The construction information mainly depends on the manual transmission of 2D drawings and documents, and the information is given to different participants in a certain order (Yang, 2017). Information is easily lost in the transmission process. It is hard for efficient cooperation to occur between participants without the support of information. The BIM functions of construction information transmission and communication have been affirmed by many researchers (Achkar, 2016; Ding and Xie, 2015). All necessary construction information is contained in the model and can be easily transmitted through the BIM platform (Chang et al., 2013). Therefore, BIM can meet the requirements of information transmission in China.

Conventional quality management lacks the necessary information accumulation (Nie, 2016). Conventional quality control finishes after defects are modified, and no more defect analysis is conducted after the end of a project (ibid.). The accumulation of quality data is rarely achieved, which results in similar defects repeatedly occurring in future projects. BIM can not only store quality data but can also retrieve previous quality information conveniently (Achkar, 2016). BIM, as a database, can support information accumulation in the Chinese construction industry.

#### **2.4.3.2 Reviewing quality-based BIM approaches**

Compared with the various BIM studies on construction costs, schedule and energy performance, there is little BIM research on quality management (He and Li, 2013). According to research on reviewing BIM research from 2006 to 2013 (Ding, Zhou and Akinci, 2014), the researches related to quality only account for 5% of all BIM-related articles. In contrast, those on cost management account for 10%, while schedule

management and energy performance both account for 17% (ibid.). When reviewing the articles published from 2014 to the present, the number of BIM articles on construction quality is still very small. There is still a lack of research on BIM and construction quality.

Within the limited research on the area, one of the most widely discussed topics with regard to BIM and quality is investigating the benefits of BIM in construction quality management. Ji et al. (2013) discuss the influences of BIM on the integrated disposition of pipes, especially in terms of the quality aspect. Defect rework was dramatically reduced by using BIM-based clash detection and construction simulation. Furthermore, BIM can collect construction information and support the collected information throughout the whole life cycle of a project (He and Li, 2013). Quality control is enhanced by the collection of abundant information (Pooyan, Griffis and Lawrence, 2009; Ding and Xie, 2015; Li, 2017). Suermann and Issa (2009) discuss the impact of BIM on construction projects. According to their research results, BIM has the highest impact on construction quality compared to time, cost and construction safety, which over 94% of the respondents believing that BIM has a strong impact on construction quality. Wang (2017) describes the quality advantages of adopting BIM in 4M1E management (which are: man and construction machines, material, method and environment). BIM is regarded as a catalyst that facilitates the integration of construction quality management (ibid.). Deng (2016) demonstrates the benefits of BIM for each construction participant during the construction process. Customers can track the construction quality status visually, while supervisors can carry out quality supervision easily through combining the BIM model and the site conditions. Contractors can also recognise potential quality defects before they occur.

The researchers (Kim et al., 2015; Park et al., 2013; Wang et al., 2015) also focus on investigating BIM-based quality inspection. BIM is used as a powerful tool to provide an object-oriented parametric model and is an integrated foundation that can be combined with other techniques. Based on findings to date, the current research on BIM-based quality inspection has made some achievements on linking BIM with other techniques such as 3D laser scanning, AR and image-matching.



Alongside the rapid development of BIM and scanning techniques in construction quality defect detection field in recent years, more and more researchers (Kim et al., 2015; Becerik-Gerber et al., 2011; Wang et al., 2015; Wang et al., 2016) have begun to focus on integrating BIM and 3D scanning techniques to enhance construction quality inspection. BIM is used as a central data repository to generate and store necessary data (Kim et al., 2015). 3D laser scanning can be adopted to collect on-site quality information and generate as-built models (Becerik-Gerber et al., 2011). Kim et al. (2015) present an integrated BIM-3D scanning system to collect geometrical information automatically and to compare the collected information with the original BIM model. In this system, BIM is also used to store construction data and acts as a data library. Wang et al. (2015) report that BIM and light detection and ranging (LiDAR) techniques can be combined to enhance the construction quality inspection process. LiDAR is a kind of 3D laser scanning technique. The highlight in Wang et al.' research is that quadrotors are adopted as carriers for LiDAR system. Similarly, based on a case study, Wang et al. (2016) propose an integrated approach which combines BIM and terrestrial laser scanning (TLS) techniques to improve construction quality inspection. New estimation algorithms are developed using these techniques to improve the efficiency and accuracy of on-site quality data collection. BIM is used as a platform to store quality information and as a reference to compare this information with the on-site as-built models generated from TLS. The approach of combining a robotic total station and BIM to improve quality control is proposed by Julian et al. (2012). In this case, information such as survey points is generated from the BIM model and transmitted to a total robotic station. The quality of lofting work can be improved through a detailed and accurate measurement by a total robotic station. Furthermore, as-built models are generated through on-site as-built point information that is scanned by the total robotic station. Managers can conduct revised work based on comparing the on-site as-built model and the original BIM model.

The AR technique is used to overlap virtual information with the real world (Park et al., 2013). Using this technique, both virtual images and real-world images can exist in the user's vision. The deviations between the real site images and the virtual images

can be easily detected through AR techniques. Additionally, in situations where differences cannot be detected by the naked eye, image-matching techniques are usually used in conjunction with AR technology. Image-matching is a technique to find differences between images. Park et al. (2013) propose a framework that combines BIM, AR and image-matching techniques to improve construction inspection. BIM-based AR inspection can improve the manual inspection process. Similarly, Kwon et al. (2014) present an approach of integrating BIM, AR and image-matching techniques to solve the issues of inspection omissions, time-consuming manual inspections and the heavy workload of site managers. Lou et al. (2016) have conducted a study on the potential use of integrating BIM and AR technologies in complex urban projects. The functions of BIM in different quality control processes and the integration of mobile AR techniques and BIM are discussed in the research.

Studies on BIM quality platforms are common among recent research on BIM and quality. BIM provides a way of storing information about defects and sharing the defect status with other participants in a 3D virtual environment. All of the related text information and on-site photos can be stored in the BIM model (Ma et al., 2016). Chang et al. (2013) have developed a mobile BIM-assisted management system to improve defect collection and storage in construction inspections. The inspection results are inputted through tablets and transferred to a BIM-related database. Tsai et al. (2014) also propose a similar approach to integrating BIM, data platforms and mobile devices. The research of Tsai et al. goes further in generating inspection plans through BIM. Chen and Luo (2014) have pushed the research on BIM quality platforms to a higher level. More specifically, the product, organisation and process (POP) model are involved with BIM to provide more detailed quality control information, and this approach impacts future research on a quality-based BIM platform (ibid.). Ding et al. (2014) share a similar idea of integrating a 4D BIM and POP model as Chen and Luo. Lee et al. (2014) focus on adopting a 4D BIM and POP model within infrastructure construction projects (such as highway construction and bridge construction). Lee et al. (2016) present a linked data system framework for storing and sharing defect data, which is a novel approach to structuring and grouping defect information based on defect categories. The research of Lee et al. focuses on

improvements to data storing and sharing mechanisms. Lin et al. (2016) have developed the BIM-based defect management (BIMDM) system to improve quality inspection. Tablets are adopted to record the inspection results. Ma et al. (2016) propose a comprehensive system to enhance the quality inspection process based on previous research. Inspection requirements are automatically generated in this system, and inspection results are recorded through mobile devices. The inspection results are stored in the system using different colours according to their quality conditions. Achkar (2016) proposes a novel 4D BIM-based quality management approach to solving the current issues with quality control, quality assurance and communication protocols in the construction industry. Inspection results are stored in order to provide experience for similar works in future projects, which should be regarded as progressive and proactive quality management.

Recently, some researchers have turned their attention from detailed BIM applications on improving construction quality to the influence of BIM on quality management (Yang, 2016; Xu, Xiong and Zheng, 2016). With the development of BIM technology, more and more cases show that without a good management philosophy, BIM cannot fully play its role in quality improvement. Yang (2016) adopts an updated PDCA (plan, do, check and action) cycle to fit the application of BIM. BIM-based construction processes are presented within a case study. Xu, Xiong and Zheng (2016) share a similar opinion as Yang and propose an optimisation process of BIM-based construction processes. Additionally, some researchers place emphasis on discussing the relationships between BIM and quality management through three stages: before-construction control, during-construction control and after-construction control (Chi, 2016; Zhou, 2016; Yan, 2017). Although the effects of BIM on quality management are briefly described, these studies still provide some implications in the exploration of BIM and quality management. However, from the reviewing exist literature discussed above, it can be found that few studies combine BIM and quality management. More research is needed on BIM from a management perspective in terms of quality improvement.

According to the results of the literature review, some quality improvements are

achieved from the model itself, which is due to the mechanisms of BIM, such as visualisation. Some construction quality improvements are achieved by conducting BIM related activities, such as BIM-based inspection. The essence of BIM-based quality activities is driven by BIM mechanisms. Quality-based BIM mechanisms provide the basis for potential BIM-based quality improvement application. Therefore, the quality-based BIM should be concluded in two aspects: mechanism aspect and application aspect. The potential quality-based BIM mechanisms and quality-based BIM applications are summarised and discussed below. The items listed in the following text have been phrased with care to express bare mechanisms and applications. The potential quality-based BIM mechanisms and quality-based BIM applications identified from the literature review were the foundation of developing interview template which related to BIM and construction quality. Moreover, the final quality-based BIM mechanisms and quality-based applications in interaction framework were concluded through literature review results and case study results.

### **1) The potential BIM mechanisms for construction quality improvement**

According to the literature review, few researchers discussed the BIM mechanisms for construction quality improvement. Some of these potential quality-based BIM mechanisms are directly summarised from the existing literature and the others are inferred from author's intention in existing literature. The potential quality-based BIM mechanisms summarised from the existing literature are listed in Table 8.

Table 8: Potential Quality-based BIM Mechanisms Summarised from the Existing Literature

<b>No.</b>	<b>Potential quality-based BIM</b>
1	Visualisation
2	Simulation and calculation
3	Dynamic
4	Collaboration
5	Integration
6	Coherence

#### **(1). Visualisation**

The application of 3D BIM visualisation in the construction industry can have a

profound impact on the upgrading of construction quality. 3D visualisation can provide the construction industry with benefits that 2D drawings cannot provide (Chi, 2016). Spatial cognition is relatively difficult for construction workers using traditional construction methods, especially for complex construction projects (He and Li, 2013). Spatial relationships are difficult to illustrate in a 2D drawing. It is also difficult for on-site construction workers to understand the designer's intention through 2D drawings. Traditional 2D-based construction requires on-site workers and technicians to visualise spatial relationships in their minds, which requires rich experience (He, 2014). Furthermore, complex and unique architectural components can exist in large construction projects. When these components are expressed through 2D drawing lines, it is hard to imagine the actual 3D shapes (ibid.). Moreover, 2D-based traditional construction can not only be inconvenient for the designers and constructors but can also cause difficulties for the customers. Customers who lack professional construction knowledge may find it hard to fully understand a project through 2D drawings. This will affect the customers in making the right decisions (He, Wang and Ying, 2012). A visual BIM model could remedy this situation. A 3D model provides an intuitive way to present spatial relationships, which reduces the difficulty in understanding a project.

Although there are some 3D rendering techniques such as 3D Max and CAD that can achieve 3D visualisation, there is still a need to access the actual construction information. The detail information of each object cannot be seen in these 3D renderings (Lu, 2017). In contrast, all of the objects in BIM can be visualised, and each object can be displayed independently. Moreover, BIM-based visualisation provides a way to implement quality control for complex nodes. Due to the complex characteristics of special shape, complicated structure and huge volume, some construction nodes are prone to quality problems in the construction process. These complex nodes are key points, which contractors should pay attention to (Ding and Xie, 2015). In fact, the construction structure of each complex node can be viewed in detail in the BIM. Additionally, detailed node drawings, including the node information profile can also be provided by the model. Managers and workers can view the node from any angle, which deepens the understanding of complex construction nodes before construction (Li, 2016). The visualisation of BIM provides

convenience for on-site workers and managers and improves construction quality.

## **(2). Simulation and calculation**

With regard to quality, BIM technology is well-known for its simulation abilities (Ding and Xie, 2015). BIM simulation can be used to identify the best practices. 4D BIM is achieved by involving a time schedule in the model. All construction activities in a project can be simulated in advance with pre-set 3D model information and a time schedule (Lu, 2017). The benefits and drawbacks of construction plans can be identified through dynamic simulation. Construction simulation in BIM is also used to anticipate the problems that may be encountered during the real construction process so that they can be modified accordingly (Zhao and You, 2015). The best construction plan is usually chosen based on simulation results. The quality of construction plans is ensured by BIM. Additionally, revised activities can also be simulated. The most appropriate revised plan can be achieved via BIM simulation. Roaming within BIM provides a virtual 3D environment. Using manual controls or a set route, a simulated human can walk around the virtual building (Lu, 2017). The environment in the building can be seen in a 3D space without restriction through the view of the simulated human. Design defects which have not been detected by clash detection can be checked through roaming. In this way, the design result can be further optimised (He, Wang and Ying, 2012). Furthermore, roaming in BIM provides an intuitive way to present the design result from all angles without viewing any dead angles (Ding and Xie, 2015). The indoor space and the spatial layout are also experienced through the intuitive presentation.

BIM has its own calculation mechanism which can calculate the rationality of construction objects within a space. The cross collision between entities can be calculated through BIM and design drawings can be checked again in BIM. Therefore, the quality of the design can be ensured.

## **(3). Dynamic**

Construction is a kind of continuous process. The information involved in construction is not fixed. All construction information needs to be constantly inputted, modified,

deleted or updated throughout the whole construction process (Achkar, 2016). As construction proceeds, the information about quality changes dynamically (Ding and Xie, 2015). Conventional information management cannot support the requirements of the timely retrieval and recording of information (Zhou, 2016). BIM can facilitate dynamic, integrated and visualised information management.

#### **(4). Collaboration**

BIM enhances collaborative working environments from a technical perspective. BIM improves construction information transmission and sharing and avoids information isolation and barriers across all life cycle stages of a project (Rao et al., 2017). An information-based visual BIM model facilitates communication between different project stakeholders, which helps faster and better decisions to be made (Zhou, 2016). BIM helps construction collaboration by improving the communication between participants, enhancing visual exhibition, enriching construction databases and strengthening parametric 3D interaction (Liu, 2016). BIM provides a platform for communication and cooperation through a visual model. Remote communication can also be achieved through the BIM platform. The BIM model, as well as construction drawings, data and documents, can be viewed in this platform. Additionally, each participant inputs and extracts construction information from the same information platform, which reduces the duplicated input of information and avoids redundancy, ambiguity and errors within the data (Zhao and You, 2015). BIM meets the needs of owners, contractors, designers, government departments and suppliers regarding browsing, communicating and sharing construction information.

#### **(5). Integration**

BIM is an integrated platform which not only involves BIM technology itself, but it can also be combined with other techniques to improve construction quality. BIM, as an information database, provides a platform for the integration of other techniques, such as 3D laser scanning techniques, AR techniques and 2D barcode techniques. Integrated application can improve the accuracy of construction work and reduce the quality inspection omission (Wang, 2013).

The 3D laser scanning technique is a widely-applied technique in construction projects. The integrated application of BIM and 3D scanning techniques is an approach to construction quality control (He, 2014). The digital model of a building can be created through 3D coordinates obtained by scanning the surface of the building (Kim et al., 2015). The digital model contains only 3D coordinates. The digital model is then uploaded to the technical team and translated into a laser point cloud model through computer modeling (Wang, 2013). This point cloud model can then be used to compare it with the BIM model. Deviations between the two models can be found and revised. Quality defects are eliminated before they transfer to the final customer.

BIM can also integrate with 2D barcode techniques. 2D barcodes can be generated through the BIM model and attached to each floor of a building (Kwon et al., 2014). On-site workers can use mobile devices to scan these 2D barcodes and access a detailed BIM model of the floor (ibid.). This model contains information about defects, such as quality categories, images of defects, detailed descriptions of defects and inspection information about defects (Chi, 2016). The 2D barcode technique can improve model responsiveness and make model lightweight because only the BIM model of the floor is displayed. The efficiency and the convenience of quality information retrieval are also improved by the integrated application of BIM and the 2D barcode technique (Zhou, 2016). Furthermore, the 2D barcode technique can help managers to track the materials used on construction site (Li, 2017). Each material has its own barcode. When materials arrive at a construction site, all of the information can be entered via the barcodes. On-site workers can scan the barcodes and send up-to-date information about the material conditions to the BIM platform which let managers understand the situations of materials as they are used. (Li and Liu, 2016).

The AR technique is used to provide construction guides in construction sites. AR can present BIM models in the real world which means both virtual images and the real-world environment overlap (He, 2014; Park et al., 2013). Using this method, on-site workers can understand the construction location, size and shape before construction begins. Moreover, the differences between the as-built work and the planned work can be easily detected through BIM-based AR techniques. Omissions and size errors can



be found by workers and managers (Kwon et al., 2014).

From the perspective of information integration, BIM is a technology with integrated information which contains not only 3D geometrical information and descriptions of spatial relationships but also information like building object names and categories, structure types, the physical and structural performance of construction material, the construction process, costs, quality, safety, the information of construction operators and mechanical and material resources (Chi, 2016). The information contained in BIM is all related to construction quality management. BIM is an integrated information library.

#### **(6). Coherence**

As construction information is updated alongside the construction process, the information in BIM models needs to be updated and revised at periodic intervals. Moreover, the information also changes when design changes occur. The mechanism of coherence results in all of the objects information in the model interacting. The information in BIM can be modified at any time and the whole model updates automatically to adapt to the modifications which mean manual adaption is not usually needed (Chi, 2016). The linked building objects change automatically when the information for one object changes. The results are also presented in a 3D model view. The mechanism of automatically update in BIM according to modified information is a benefit of BIM. This mechanism maintains information coherence and reduces inconsistent information errors (Wang, 2017). The quality of construction is improved with a coherent model.

#### **2) The potential BIM applications for improving construction quality**

The potential quality-based BIM applications are summarised from the existing literature (see Table 9) and discussed below.

Table 9: Potential Quality-based Lean Construction Theories Summarised from the Existing Literature

No.	Potential quality-based lean construction theories
1	BIM-based clash detection
2	BIM-based construction plan simulation and optimisation
3	BIM-based quality inspection

### **(1). BIM-based clash detection**

Clash detection refers to the inspection of drawings before the actual construction begins (Ji et al., 2013). It is used to detect clashes between different disciplines, such as structural engineering, mechanical, electrical, and plumbing (MEP) engineering and environmental engineering (Fu, 2017). These clashes are usually regarded as incompatible parameters, overlapping spatial elements and elements that are too close (Lu, 2017). Conducting clash detection via traditional 2D CAD drawing is not easy and requires a large number of drawings, personal understanding of spatial information and work experience, as well as discussions of the collisions with engineers from various disciplines (Fu, 2017). The drawbacks of traditional clash detection are obvious: it is time-consuming, abstract spatial thinking is required, the risk of incomplete records and the overlay of drawings can be messy (Li, 2015). If these problems are not properly dealt with, the quality of the buildings will be affected.

Compared with traditional clash detection, BIM-based clash detection has many advantages in terms of improving quality. BIM can integrate models from different disciplines together and detect clashes automatically (Lu, 2017). Furthermore, BIM can provide sectional views for any of the elements in the model. These detailed views are conducive to understanding the collision results (Li, 2015). Moreover, BIM can provide an intuitive approach to review design, such as utilising roaming to observe a building from the inside (ibid.). It also can reduce clash collision in a visual way.

### **(2). BIM-based construction plan simulation and optimisation**

Traditional construction plan in China is usually undertaken according to 2D design drawings and the planners' construction experience (Yang, 2013). The subjective aspects of project managers, such as their work experience and understandings of

construction schedule plans, construction abilities and the construction environment can affect the quality of construction plans (Kong, 2017). Traditional construction plans are not always suitable for the actual field conditions and for guiding the actual site construction due to personal limitations (Lu, 2017). Furthermore, with the development of construction projects, new construction techniques and materials usually need to be adopted in the projects due to different customer's requirements. The traditional planning approach, which mainly relies on 2D design drawings and text descriptions, makes it difficult for project managers to introduce the steps and the procedures for implementing new materials and processes clearly (Chi, 2016). Construction workers and technicians may also struggle to understand these plans (ibid.). Furthermore, because of a lack of experience, it is hard to introduce a reasonable plan for new technologies and the application of new materials straight away (Kong, 2017; Chi, 2016).

4D construction simulation can be carried out by linking a progress plan with a 3D BIM model. The advantage of 4D construction simulation is that it can simulate a whole plan by connecting it to a timeline. Planners can have a reasonable understanding of the whole plan by reviewing the 4D simulation results. The 4D simulation also presents the quality control points in the construction procedure, which increases the efficiency of quality control (Kong, 2017). Furthermore, the dynamic virtual construction process can be observed intuitively through 4D BIM construction simulation (He, Wang and Ying, 2012). It can discover the conflicts between the construction teams in time and space in the cross work in time (ibid.). Construction plans can be repeatedly verified and adjusted through construction simulation.

### **(3). BIM-based quality inspection**

The emergence of BIM technology has provided the ability to 'build on computers'. Inspection plans can be generated through BIM and distributed to on-site construction managers (Ma et al., 2016). On-site managers can integrate quality data collection techniques and BIM to obtain the current quality status of a site. Construction managers can upload real-time data on construction quality directly through mobile devices, which can transmit quality information quickly and correctly (Kwon et al.,

2014). The on-site data on the construction quality and the BIM model can be compared to identify deviations. Modification notifications can then be distributed to the on-site construction managers.

#### BIM optimises quality inspection plans

BIM-based inspection plans are generated by analysing the project quality requirements, the current construction work, the national inspection standards and the construction schedule with the assistance of BIM technology. BIM contains all of the physical information and the information of the functional requirements by the customer (Ma et al., 2016). General quality requirements can be divided into detailed quality requirements for each building component according to physical information, the functional requirements and the quality requirements of construction measures (Wang, 2013). Each component has its own specific quality requirements and parameters which this information is stored in BIM and prepare for supporting quality inspection plan design. Inspection plans are generated by considering the current construction processes (Ma et al., 2016; Achkar, 2016). The inspection tasks and locations are presented through the BIM model to guide the quality inspection work being undertaken on-site (Tsai et al., 2014).

#### BIM changes the way of on-site quality information collection

Quality information collection is an important process for improving construction quality. The BIM-based quality information collection methods should be selected according to the current on-site conditions. The basic collection methods in China include digital photography and video camera techniques (He, 2014). These methods are suitable for simple environments in which the defects are obvious (ibid.). Additionally, these defects can be reported alongside text captions to describe the details. However, if the construction site conditions are relatively complex, particularly the construction components are complicated, and the construction site is disorderly, these basic collection methods should be supplemented with other techniques. 3D scanning techniques, AR techniques and 2D barcode techniques can be used to collect information (Zhou, 2016).

3D laser scanning is one of the most reliable techniques among BIM-based quality information collection methods. Dimensional and surface quality information can be captured through 3D laser scanning techniques (Kim et al., 2015b). TLS techniques provide a way of obtaining quality information from irregular geometrical objects (Wang et al., 2016). Moreover, quadrotors can be used to improve the real-time on-site data collection process. The application of quadrotors can prevent humans from having to undertake some dangerous on-site quality data collection work (ibid.). Additionally, the difficulty of taking measurements in huge projects can be solved by adopting quadrotors to conduct 3D laser scanning. The scanned data can be transmitted to a computer to build a digital model. This model can then be compared with the BIM model.

AR techniques and BIM are integrated applications that improve construction quality. The relevant information from defect inspections through BIM can be converted into AR markers. These AR markers can be attached to assigned inspection locations. Augmented BIM geometry information can be viewed by on-site workers through AR applications on their mobile devices (Kwon et al., 2014). Screenshots can be taken through the AR applications, and the images are automatically sent to site managers. The deviations between the virtual plan and the real conditions can be recognised. The AR technique provides an effective way of detecting dimension errors and omissions with the help of augmented BIM geometry information (Park et al., 2013). It also supports automatic dimension checks, which can reduce site managers' workloads.

2D barcode techniques in quality inspection can be used to make BIM models lightweight and improve their responsiveness. 2D barcodes contain BIM information and workers attach these barcodes to assigned areas. Tablets can be used to scan the 2D barcodes to load 3D BIM models, which contain the inspection information for the specific area or floor. All of the necessary information is stored in the 2D barcodes and can be accessed during inspections. The information related to defects such as defect categories, images of defects, detailed descriptions of defects and the inspection process is uploaded through mobile devices. The 2D barcode technique improves the operating speed and the speed of the transmission of quality information on mobile

devices through a lightweight BIM model.

BIM changes the way that quality information is compared

The collected quality data can be compared in two ways: foreground contrasting detection (On-site comparison) and background platform contrasting detection (Database comparison) (Tsai et al., 2014). Inspectors can obtain quality information from BIM models through mobile devices and can compare it with the on-site situation which means this process is not dependent on personal understandings of spatial information and construction experience. Utilizing model information, construction specifications and quality acceptance specifications, real-time comparative analysis can be carried out (Lu, 2017). Construction quality acceptance records which meet the requirements of quality standards can be uploaded in a timely manner and nonconformance reports are also generated for detected quality defects (Li, 2016). The information of the defect situation, the inspection time, the weather and the defect location are inputted into the BIM model after defects are detected (ibid.).

When situations like complicated inspection components, disorderly construction sites, irregular geometrical surfaces and dangerous inspection areas are encountered, defect detection works are difficult to manually complete on-site. In this situation, the collected data should be transmitted into the BIM database. 3D laser scanning can be used to develop a digital model for situations in which defect detection works are difficult to manually complete, and this digital model is used to compared with BIM model (Kim et al., 2015; Wang et al., 2016). The screenshots created from AR and the images taken on real construction sites can be compared automatically through image-matching techniques (Park et al., 2013). In this way, deviations can be discovered. These deviations are discussed under the categories of construction specifications and quality acceptance specifications (He and Li, 2013). The defects are from these deviations.

Defect information, which includes the construction situation, construction time, construction progress and defect modification methods, is stored in the BIM database (Achkar, 2016). The defect information is linked with an inspected component in the

BIM model. The components with different associated defect information are grouped according to conditions in different colors (Chen and Luo, 2014). The inspection results are visually displayed in BIM to help managers intuitively access quality information (ibid). Moreover, the model is updated in a timely manner according to the current construction progress. After modification work is finished, the status of each component changes alongside the updated defect information (Ding et al., 2014).

#### BIM-based quality modification

Quality defects can be reported in many ways, such as through text, voice clips and pictures. The relevant employees are selected according to their personal information stored in the BIM system and the information about defects is sent to these relevant employees for discussion through the BIM collaborative platform (Xiao et al., 2014). Modification plans are created through collaborative discussions and BIM-based simulations. The inspection results after the defect modification process are completely uploaded to the BIM database. All information on quality defects is updated in the model, which includes quality information on building components, construction materials and equipment, quality standards, control procedures and the responsibilities of each employee (ibid.). The defect and modification information is stored in the model and can be retrieved and accessed, providing an example for similar works in future projects (Achkar, 2016).

### **2.5 Current Research on the Integration of Lean Construction and BIM on Construction Quality Improvement Aspects**

There is a consensus in the existing literature that lean construction can improve construction quality. Moreover, BIM is a revolutionary tool that greatly impacts construction quality. Although the applications of BIM and lean construction are not dependent on one another, it is hypothesised by researchers (Liu and Shi, 2017; Shi, 2015) that the full potential for their integration on construction quality improvement can only be achieved through the integrated application of lean construction and BIM. The previous research on the integration of lean construction and BIM to improve construction quality is presented and discussed in this section.

Liu and Shi (2017) point out that BIM and lean construction have gradually been combined and applied in China in recent years. The impacts on the quality of this integrated application have gradually caught researchers' attention. A new framework of KanBIM construction quality control is proposed in this study. The LPS and BIM are combined to provide a foundation for a KanBIM quality system. The positive results reported in a case study demonstrate that the integrated application of lean construction and BIM can bring benefits to construction quality.

Laine, Alhava and Kiviniemi (2014) emphasise the importance of information management in built-in quality management. Visual management within lean construction philosophy and BIM are integrated to ensure information quality. In this study, it is recognised that BIM cannot solve all quality problems, but it does provide a tool for the new process. Visual management is a new process to manage information. The result of combining visual management and BIM is the Software-based Standardised Model Views system (SMVs). According to evaluation in their research, the use of the SMVs increases built-in quality.

Dave (2013) has developed a construction management system called VisiLean, which is based on lean construction and BIM. This new system absorbs the benefits of both lean construction and BIM. Although quality management is a function that is not part of the VisiLean system, the impact of the integrated application of lean construction and BIM on construction quality improvement is affirmed by Dave. Some other functions of VisiLean also indirectly improve construction quality.

Shi (2015) analyses the interactions between BIM and lean construction and proposes a framework based on the LPS and BIM to control construction defects. It is suggested that IPD is applied to facilitate the integration of LPS and BIM.

It is also agreed by Bi and Jia (2016), and Ningappa (2011) that the integrated application of lean construction and BIM is indispensable in construction quality improvement. The synergy between BIM and lean construction changes team coordination and workflow. Construction projects benefit from these construction



processes changing (Clemente and Cachadinha, 2013).

There is a consensus in the previous literature that integrating lean construction and BIM in the construction process can improve construction quality. However, the findings of the existing research are mainly related to recognising the importance of integrating lean construction and BIM for construction quality improvement. Furthermore, some studies on integration are carried out for specific aspects (See Table 10), such as the LPS and BIM-based quality information management (Shi, 2015), the LPS and BIM-based construction plan simulation and optimisation (Liu and Shi, 2017), kanban and BIM-based information management (ibid.). However, these interactions are not directly proposed but to be inferred from the author's intentions. There still lacks systematic exploration to directly describe the interactions of lean construction and BIM from a quality improvement perspective. Further efforts are needed to bridge this gap in knowledge, which is the focus of this research.

Table 10: Potential Quality-based Interactions between Lean Construction and BIM Summarised from the Existing Literature

Quality-based Interactions between lean construction and BIM	
1	LPS and BIM-based quality information management
2	LPS and BIM-based construction plan simulation and optimisation
2	kanban and BIM-based information management

Some interactions were validated by the existing literature, such as the LPS and BIM-based quality information management (Shi, 2015), the LPS and BIM-based construction plan simulation and optimisation (Liu and Shi, 2017), kanban and BIM-based information management (ibid.).

## 2.6 Summary

As the results of the literature review, the current Chinese construction quality situation is not good, which needs to improve. The Chinese construction quality improvement +requirements are summarised as ‘prevention mentality’, ‘long-term consideration of quality-oriented mindset change’, ‘win-win cooperation’, ‘continuous improvement of standardisation’, ‘collaborative plan’, ‘prioritising customer requirements’,

‘continuous information requirement’ and ‘motivation management’. Furthermore, five potential quality-based lean construction theories and four potential quality-based lean construction techniques are identified in this chapter. Additionally, six potential quality-based BIM mechanisms and three potential BIM applications are presented from reviewing literature.

From reviewing results of BIM, lean and quality, there lacks research on integrating lean construction and BIM to improve construction quality. According to literature review results, there is no research effort has been conducted to comprehensively research the interactions of lean construction and BIM on improving construction quality.

## Chapter 3: Research Methodology

### 3.1 Introduction

The research design, techniques and methods are discussed in this chapter. The aim of this chapter is to justify the chosen research methodology, method and data collection techniques, and provide a detailed adoption process description.

Currently, there is no existing literature that comprehensively investigates the quality-based interactions between lean construction and BIM., As Saunders et al. (2007) stated, exploratory research is suitable for investigating unknown knowledge. Therefore, exploratory research was adopted in this study. As identified through the literature review, more in-depth investigation in this area is required. According to Thomas (2003), qualitative research is one efficient way to investigate unknown topics. Case studies and surveys are powerful methods to obtain the views of professionals. These methods can help the researcher to achieve their research aim. The findings of the literature review in this study informed the selection of the research methodologies, methods and data collection techniques, and the influences are further discussed alongside the justifications for each research method. Table 11 provides an overview of the research methodologies adopted in this study.

Table 11: Summary of Research Methodology

Research methodology	Adopted in this research
Research philosophy	Realism ontology and interpretivism epistemology
Research approach	Qualitative research
Research design	Case study and survey
Data collection technique	Data collection techniques in case study <ul style="list-style-type: none"><li>• Documentation</li><li>• Directly observation</li><li>• Interview</li></ul> Data collection technique in survey <ul style="list-style-type: none"><li>• Interview</li></ul>

### 3.2 Research Philosophy

A research philosophy is an assumption of the way to develop knowledge (Saunders et al., 2015). It provides the basis for selecting research approaches and methods. A research philosophy is used to decide which particular research approaches should be

adopted by the researcher and why (Thakurta, 2015). There are two major approaches to research philosophy, which are ontology and epistemology.

### **3.2.1 Ontology**

According to Saunder et al. (2015), ontology refers to ‘assumptions about the nature of reality’. There are two aspects to ontology: realism and relativism. An assumption is proposed in ontological realism that the external world is comprised of pre-existing tangible structures (Liu, 2014). As Thakurta (2015) states, ‘the core feature of realism is pertained to disclose the truth of reality and the existence of the objects are prevalent independently in the human mind’. The aim of ontological realism is to provide an account of the nature of scientific practice (Bryman, 2008). Relativism is practical and unconcerned with the abstract or the idealistic view of life. From the perspective of relativism, all points of view are valid from a particular perspective. Ontological relativism is mainly associated with the truth, knowledge and morality.

### **3.2.2 Epistemology**

g to Saunder et al. (2015), ontology refers to ‘assumptions about the nature of reality’. There are two aspects to ontology: realism and relativism. An assumption is proposed in ontological realism that the external world is comprised of pre-existing tangible structures (Liu, 2014). As Thakurta (2015) states, ‘the core feature of realism is pertained to disclose the truth of reality and the existence of the objects are prevalent independently in the human mind’. The aim of ontological realism is to provide an account of the nature of scientific practice (Bryman, 2008). Relativism is practical and unconcerned with the abstract or the idealistic view of life. From the perspective of relativism, all points of view are valid from a particular perspective. Ontological relativism is mainly associated with the truth, knowledge and morality.

This research was intended to investigated the potential quality-based lean construction approaches and quality-based BIM approaches and to research the interactions between these two approaches. These research objectives were achieved through exploring, eliciting and understanding the views from individuals in the construction industry. Hence, the data collection objective in this research was

exploratory in nature, and the open-end questions were needed to be used in research. As Creswell (2014) states, the interpretivism epistemology benefits for collecting rich data through qualitative approaches, which increase the general understanding of research subject. Moreover, the interpretivism epistemology is helpful to get a richer and deeper understanding of individuals' responses (ibid.). Therefore, as for this research, interpretivism epistemology was mainly adopted. This provides a foundation for the further selection of research approaches and research methods. The literature review was adopted to achieve the background knowledge of research topic and develop a future strategy for research. This positioned the research within realism ontology. The whole understanding of the world starts with the existing knowledge.

### **3.3 Research Approaches**

#### **3.3.1 Quantitative research**

Quantitative research is related to positivism (Davies, 2007). It is based on the research of quantities and measurements. Statistical, computational and mathematical tools are used in quantitative research to acquire the research results. Careful sampling strategies and experimental designs are used to quantify problems and to achieve universal results (Thomas, 2003). The nature of quantitative research means that it can answer 'how' questions, such as 'how much' and 'how many' (Biggam, 2015). One of the important benefits of adopting quantitative research is that it is quick and economical. Additionally, the measurement and analysis methods are easily replicable by other researchers. The researcher also has the capability to manage a large number of samples when they adopt quantitative research. Its linear and statistical characteristics make quantitative research quite useful in evaluating existing theories.

#### **3.3.2 Qualitative Research**

Qualitative research refers, primarily, to exploratory research (Thomas, 2003). This kind of research can be used to investigate the thoughts and feelings of the research participants. It is beneficial in providing an in-depth understanding of what behaviours take place and how they do so (Sutton and Austin, 2015). Qualitative research provides insights into the drawbacks and benefits of developing theories. It is also used to uncover trends in thoughts and opinions (Hammarberg, Kirkman and Lacey, 2016).

The data collected from qualitative research cannot usually be counted or measured. According to Bryman (2008), the qualitative method is usually chosen for the following situations: 'there is no existing research data on the topic and the most appropriate unit of measurement is not certain' or 'the research concept is assessed on a nominal scale with no clear demarcation involved in exploring behavior or attitudes'. The most important benefits of adopting qualitative research are 'being able to understand from participants' and 'benefit to theory generation' (Neuman, 2006).

### **3.3.3 Mixed methods research**

It is possible to combine qualitative and quantitative research methods in a mixed methods approach. Mixed methods research refers to the conducting of research to collect and analyse data from both quantitative and qualitative approaches. The various advantages of quantitative and qualitative research can be enjoyed by adopting mixed methods research (Liu, 2014). These two approaches can be used consecutively to investigate different questions or simultaneously to investigate the same questions. The importance of applying mixed methods research is to compliance with research aim and objectives.

Choosing one type of research approach over another is based on the objectives of the research (Jankowicz, 2000). Compared with quantitative research, qualitative research is more suitable if the study aims to develop a theory or framework (Saunders et al., 2007). Although both quantitative and qualitative research are concerned with exploring phenomena, there are differences between these two approaches. Quantitative research is mainly concerned with answering 'how' questions, such as 'how many' and 'how much' (Biggam, 2015). In contrast, qualitative research focuses on the in-depth investigation of the meanings and the perspectives of the participant (Hammarberg, Kirkman and Lacey, 2016). Quantitative research is valuable in evaluating existing theories (Biggam, 2015). Qualitative research is used when there is no existing research data on a topic and it provides the potential for generating new theories and ideas (Saunders et al., 2007).

The aim of this research is to investigate the feasibility of integrating lean construction

and BIM for construction quality improvement in China and to develop a quality-based framework featuring the interaction of lean construction and BIM during the construction phase. The critical element of this research is first investigating the potential quality-based lean construction approaches and quality-based BIM approaches from the selected projects. The investigation of what the current quality-based lean construction approaches are and how these approaches are conducted was necessary. Subsequently, the incentives, limitations and requirements of lean construction in terms of Chinese construction quality improvement could be identified. The research process for quality-based BIM approaches was the same as for quality-based lean construction approaches. This research addresses the question of the reason for integrating lean construction and BIM to improve the Chinese construction industry and how the integrated relationship between lean construction and BIM can be understood from the perspective of Chinese construction quality improvement. Moreover, this research was conducted to investigate the interactions between quality-based lean construction approaches and quality-based BIM approaches and how they can be integrated. Lastly, the validation of the framework requires the assessment of whether it has worked. As the objectives of this research were to answer ‘what’ and ‘how’ questions, according to Creswell (2014), a qualitative approach should be adopted. Quantitative and mixed methods research should not be used. This research aims to create a framework to fit the requirements of the improvement of Chinese construction quality, which mainly relies on the in-depth investigation of individuals’ perspectives. This is also why qualitative research was adopted. Additionally, according to the literature review in Chapter 2, there is a lack of research on the relationships between lean construction, BIM and construction quality improvement. There was no content available on each interaction at the beginning of this research. This situation meant that quantitative and mixed methods research were not suitable. Hence, qualitative research was adopted in this study to gain insights into Chinese experts’ views and to fully understand them.

### **3.4 Research Design and Data Collection Techniques**

Research design is used to determine an appropriate approach to collecting data and

drawing conclusions, and it relates to the research objective (Fellows and Liu, 2008). According to Bryman (2008), research design is not only used to determine an approach to collecting and analysing data but also to identify the research methods for the study. Numerous research designs can be chosen. However, there are five common research design types, which are action research, ethnographic research, experiments, case studies and surveys.

#### **3.4.1.1 Action research**

Action research is usually conducted within the environment where the researcher works to solve a particular problem (Cunningham, 1995). The researcher actively participates in the study process, not just as an observer but as a participant (Biggam, 2011). Action research is usually adopted to solve particular social problems (Fellows and Liu, 2008). However, it is hard to prove its objectivity. Due to the aims of this study, changes within a social system are not included in the research scope, so action research has not been adopted in this study.

#### **3.4.1.2 Ethnographic research**

Ethnographic research is the study of culture and roots in anthropology (Fellows and Liu, 2008). Ethnographic researchers not only have to record what the behaviour is and how it occurs but also have to provide some interpretation of why it occurs (Saunders et al., 2007). Ethnographic research needs a sufficient amount of time to be achieved. As Biggam (2011) states, ethnographic research is not fit for novice researchers without clear guidance. Although the intention at the start of this study was to collect data from China, it was felt that case studies, and interviews would be more informative than recording behaviours. Therefore, ethnographic research has not been adopted.

#### **3.4.1.3 Experiments**

Experimental research is the process of testing research hypotheses through experiments (Biggam, 2011). According to Fellows and Liu (2008), experimental research is adopted in laboratories to investigate causal relationships between variables. However, it is not usually feasible for use in management research due to ethical



reasons (Saunders et al., 2007). Only captive populations (such as university students) tend to participate in experiments outside of laboratories (ibid). Further to this, because of experiments' small sample sizes, it is hard to prove external validity (Fellows and Liu, 2008). The aim of this study is to investigate the feasibility of integrating lean construction and BIM to improve Chinese construction quality, and to develop a quality-based lean construction and BIM interaction framework during the construction phase. There is no direct connection between the role of experimental research and the research objectives. Therefore, experimental research is unsuitable for this study.

#### **3.4.1.4 Case studies**

According to Robson (2002), case study research is defined as 'a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence'. Although just one or even a few cases may be studied, these studies are in-depth (Harris and Ogbonna, 2002). The aim of adopting case studies is to ensure theoretical validity. In addition, case study research is particularly useful for researchers who want to achieve a rich understanding of the research context and put forward new ideas (Morris and Wood, 1991).

As Creswell (2014) states, a research design should consider the original research objectives when identifying what data is required and how the data to be. As illustrated in Table 11, the second objective is to investigate the quality-based lean construction approaches and quality-based BIM approaches. In order to achieve these two objectives, exploratory research is needed. Therefore, the research is positioned within qualitative research. Action research, ethnographic research, case study and survey were the available options due to these could provide qualitative data. Action research is usually adopted to solve particular social problems within the environment where the researcher works (Cunningham, 1995). It was not suitable for the research topic. The research was set to explorative research which was not to solve a particular social problem within the researcher's working environment. Furthermore, ethnographic research is so complicated which is not suit for inexperienced researcher (Biggam,

2011). Therefore, ethnographic research was not accepted. This research opted to select case study as a research design approach.

According to Fellows and Liu (2008), the four uses of case study research in construction management research are:

- As a source of insights and ideas
- To describe phenomena
- Project-biography
- Illustrative anecdotes

Case study research has been adopted as a source of insight and ideas in many studies with topics similar to this study, such as Liu and Shi (2017), Alhava and Kiviniemi (2014), Hartmann (2012) and Hamdi and Leite (2012). According to this research's objectives, qualitative research is required for finding Chinese experts' insights and experiences on the quality-based lean construction approaches and quality-based BIM approaches. As information illustrated in Table 12, qualitative data is mainly obtained in case studies and in-depth investigation could be provided through a case study. Additionally, according to the advantages listed in Table 12, the question of 'how', 'what' and 'why' could be answered in a case study. Therefore, the questions of why lean construction (or BIM) could improve construction quality, what the relationships between lean construction (or BIM) and construction quality improvement are, and how lean construction (or BIM) improve construction quality was expected to be answered in the case study. Hence, the case study was regarded as one of research design approaches in this research.

Table 12: Characteristics of Case Studies (Fellows and Liu, 2008; Saunders et al., 2007; Biggam, 2011; Bryman, 2008)

<b>Terms</b>	<b>Case study research</b>
Case amount	One or a few cases
Priority of data	Qualitative data is prior
Advantages	<ul style="list-style-type: none"> <li>• Gain a rich understanding of research context</li> <li>• Generate answers to the questions of 'why?', 'what?' and 'how?'</li> </ul>

Disadvantages	<ul style="list-style-type: none"> <li>• Provide an in-depth investigation</li> <li>• Easy for students to focus their research on one or a few cases</li> <li>• Time-consuming</li> <li>• Too long results</li> <li>• Where context begins and ends</li> </ul>
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#### **3.4.1.5 Surveys**

Surveys are commonly used to collect qualitative and quantitative data over a certain period of time (Saunders et al., 2007). Survey research is usually used for exploratory and descriptive research (Bryman, 2008). It is popular due to its convenience when collecting large amounts of data in an economical way. According to Fellows and Liu (2008), there are three widely used data collection techniques in survey research, which are interviews, questionnaires and observation. Survey research is a common strategy to answer questions relating to ‘who?’, ‘what?’, ‘where?’ and ‘how?’ in management research.

According to the reasons discussed in the previous section, the action research and ethnographic research was not suitable for this research. In order to achieve the fifth objective, which was to explore the potential interactions between quality-based lean construction approaches and quality-based BIM approaches from the results of case study and literature review, case study was not accepted. A survey was used to fulfil the requirement of interaction exploration. The survey could collect both quantitative and qualitative data depends on which data collection is collected. As Tan (2002) argues, survey provides an approach for the researcher to better understand the responder’s meaning and make it easier to generate new theories. These advantages make the researcher identify possible relationships better.

#### **3.4.2 Data Collection Techniques in Case Studies**

There six research techniques that can be applied in case studies, which were proposed by Yin (2009) with strengths and weaknesses (see Table 13). Each technique has its own characteristics. There is no need to use all the techniques in every case study (Stake, 1995). However, multiple applications of these techniques could improve research reliability (Yin, 2009).

Table 13: Types of Case Study Evidence (Yin, 2009)

Source of Evidence	Strengths	Weaknesses
Documentation	<ul style="list-style-type: none"> <li>• stable - repeated review</li> <li>• unobtrusive - exist prior to case study</li> <li>• exact - names etc.</li> <li>• broad coverage- extended time span</li> </ul>	<ul style="list-style-type: none"> <li>• retrievability – difficult</li> <li>• biased selectivity</li> <li>• reporting bias – reflects author bias</li> <li>• access - may be blocked</li> </ul>
Archival Records	<ul style="list-style-type: none"> <li>• same as above</li> <li>• precise and quantitative</li> </ul>	<ul style="list-style-type: none"> <li>• same as above</li> <li>• privacy might inhibit access</li> </ul>
Interviews	<ul style="list-style-type: none"> <li>• targeted - focuses on case study topic</li> <li>• insightful - provides perceived causal inferences</li> </ul>	<ul style="list-style-type: none"> <li>• bias due to poor questions</li> <li>• response bias</li> <li>• incomplete recollection</li> <li>• reflexivity - interviewee expresses what interviewer wants to hear</li> </ul>
Direct Observation	<ul style="list-style-type: none"> <li>• reality - covers events in real time</li> <li>• contextual - covers event context</li> </ul>	<ul style="list-style-type: none"> <li>• time-consuming</li> <li>• selectivity-might miss facts</li> <li>• reflexivity-observer's presence might cause changes</li> <li>• cost-observers need time</li> </ul>
Participant Observation	<ul style="list-style-type: none"> <li>• same as above</li> <li>• insightful into interpersonal behaviour</li> </ul>	<ul style="list-style-type: none"> <li>• same as above</li> <li>• bias due to investigator's actions</li> </ul>
Physical Artefacts	<ul style="list-style-type: none"> <li>• insightful into cultural features</li> <li>• insightful into technical operations</li> </ul>	<ul style="list-style-type: none"> <li>• selectivity</li> <li>• availability</li> </ul>

#### 3.4.2.1 Documentation

The different types of documents are summarised by Yin (2009): memoranda, emails, agendas, announcements, meeting records, written reports and administrative documents (such as proposals and progress reports). More and more types of documents, such as online resources, have become apparent in recent years. These types of documents are useful in providing the background information of a case study. The advantages and disadvantages of documents are listed in Table 13.

Document analysis was selected for three reasons. Firstly, documents can provide the

basic background information of a case study or a company (Yin, 2009). The information collected through documents is related to other data collection techniques, such as interviews. Secondly, document analysis offers the opportunity to compare data collected using this method with other evidence collected from other data collection techniques (Rohlfing, 2012). Further research can be conducted if the evidence is contradictory. Thirdly, the researcher can draw inferences from documents (Yin, 2009). New insights can be revealed by asking questions about the documents. Due to the value of documents, this data collection technique was used in this case study.

#### **3.4.2.2 Archival records**

Compared with documents, archival records are not always available to the public (see Table 13). There are many types of archival records, including public use files, service records, organisational records and survey data (Yin, 2009). The researcher should carefully consider the archival records' accuracy and relevance to the research topic.

#### **3.4.2.3 Interviews**

Interviews are used to collect verbal information in a systematic way (Evans, 2007). This is one of the most important ways of getting information in a case study. The interviews in a case study are more likely to be fluid than rigid (Yin, 2009). The researcher needs to ask the interviewees the prepared questions in an unbiased manner. It is important in interviews to guide the conversation rather than only asking structured questions.

One of the most commonly used types of interview is semi-structured interviews. These interviews allow researchers to extract useful information from different kinds of interviewees. The interviewees can be encouraged to propose their insights into certain topics. Structured interviews use more structured questions (Thomas, 2003). The interviewee is asked a particular set of predetermined questions. All of the interviewees are asked the same questions in the same order. The questions in structured interviews are closed-ended, offering the interviewees a limited range of options when answering the questions (Moore, 2006). Structured interviews are not flexible and not fit for providing answers to questions about unknown issues (Evans,

2007).

Interviews are regarded as an essential source of evidence in case studies. The characteristics of a case study, such as dealing with individuals' affairs and behaviours, mean that interviews are essential (Clough and Cath, 2012). A well-processed interview can obtain some in-depth insights from interviewees that are not expected before the interview (Moore, 2006). Interviews can not only provide answers to the questions of 'what' and 'how' but also to 'why' (ibid.). Structured interviews feature many closed-ended questions, which limit the width and depth of interviewees' answers (Yin, 2009). It is difficult to identify and discuss unexpected issues using this type of interview. Semi-structured questions are commonly used in interviews to collect data on attitudes, feelings and behaviours (Moore, 2006). This kind of interview can provide rich data from the interviewees if it is processed well and is organised. The interview process is more flexible than structured interviews and some questions should be asked according to the interview situation (Evans, 2007). These questions that are not predetermined should be raised spontaneously in a free-flowing conversation. Therefore, non-predetermined questions are suitable for collecting an interviewee's viewpoint on a particular situation. Semi-structured interviews are suitable for exploratory research. Therefore, due to the exploratory requirements of the data collection in this study, semi-structured interviews were selected for this research.

#### **3.2.4.4 Direct observation**

When a researcher needs to participate in a case study, they will have the opportunity to directly observe the subject being studied. According to Yin (2009), relevant behaviours and environmental conditions can be observed through direct observation. Direct observation can be conducted in casual or formal ways. The direct observation in this case was not only the observation of the construction field, such as through field visits, but also the observation of construction participants, especially through interviews.

Compared with participant observation, direct observation provides evidence without much risk of potential bias. Direct observation provides the opportunity to understand

the characteristics of a research project in a direct way. The role of the researcher in direct observation is an observer who records phenomena without bias and raises questions about the results of the observation (Yin, 2009). It is quite important to obtain first-hand data through observation (Evans, 2007). Participant observation was not adopted in this research as there may not have been enough time for the observer to record the data or to raise questions while participating in a research activity. Additionally, the work area may have been physically dispersed. This situation could cause the observation to be one-sided and it may have been difficult to generate the observation for the whole project. Thus, direct observation was selected.

#### **3.2.4.5 Participant observation**

Participant observation is a specific type of observation which observatory participants into the project (Yin, 2009). Social interaction between the researcher and the project participants is associated with this kind of observation (Evans, 2007). The researcher is not only a passive observer but also has a role in works that are related to the research topic. Regarding the weaknesses of participant observation, the potential biases when adopting this kind of observation should be considered.

#### **3.2.4.6 Physical artefacts**

Physical artefacts, such as technological devices, tools and instruments, can provide physical evidence in case studies. However, according to Yin (2009), this method has little potential relevance in most case studies.

The data collection techniques are selected according to the researcher's ability to control data, the confidentiality of data (Yin, 2009), the aim and objectives of research and the willing of the researcher (Rohlfing, 2012). Therefore, the interview, direct observation and document were selected as the main data collection techniques for the case study. Another source of evidence like archival record was also attempted but to be treated as secondary evidence due to the difficulties of getting confidential data.

### **3.4.3 Data Collection Techniques in Surveys**

The techniques adopted in surveys mainly take a deductive approach to research. Both quantitative and qualitative data can be obtained through surveys (Axinn and Pearce, 2006). The main data collection techniques used in surveys are questionnaires, interviews and observation. As the purpose of a survey in this research is investigating the interactions between quality-based lean construction approaches and quality-based BIM approaches, as identified by the case study and literature review, observation was not suitable for this research. The data collection techniques in survey are selected between questionnaire and interview.

#### **3.4.3.1 Questionnaire**

Questionnaires are usually adopted to collect quantitative data in survey research. It is quite a popular data collection technique. The participants normally analyse the questions and assign numerical values to their answers, using Likert-type scales, for example (Thomas, 2003). The participants can complete the questionnaires at a convenient time and have enough time to think about their answers. However, questionnaires can be passive and result in the researcher missing the finer nuances of the answers (McBurney, 2001). Moreover, the risk of a low questionnaire response rate should be seriously considered. The participants could refuse to respond to the questionnaires for a number of reasons. It could be difficult to encourage the respondents to respond to the questionnaires without directly conversing with them. Additionally, questionnaires are quite useful for investigating the performance of existing theories but not for exploring new theories (Yin, 2009).

#### **3.4.3.2 Interview**

The data collection method of interviews in surveys is used to collect qualitative information from interviewees in a similar way to interviews in case studies. The characteristics, benefits and types of interviews are discussed in the above section on the data collection techniques used in case studies. For this reason, this section does not repeat this information.

This research aims to investigate and identify the interactions between quality-based lean construction approaches and quality-based BIM approaches, which requires



qualitative data. According to the comparison between questionnaires and interviews in Table 14, compared with questionnaires, interviews are more suitable for complex situations and are useful for collecting in-depth information. As explained by Yin (2009), interviews are usually adopted for exploratory research. This research is a kind of exploration that aims to investigate the interactions between two approaches. Interviews should be regarded as a data collection technique in surveys. Additionally, conducting questionnaires as part of survey research would have been difficult in this study as it would have been hard to form effective questionnaire questions that were detailed enough. This study is exploratory and the existing research on the same topic is not mature. The limited knowledge in the existing literature would have made it difficult to form an effective questionnaire. Moreover, all of the respondents to the questionnaires would be anonymous, which could influence the authenticity of the questionnaires. As mentioned above in the previous discussion on data collection and selection for case studies, semi-structured interviews are suitable for fulfilling the requirement of collecting in-depth qualitative data. Therefore, semi-structured interviews were adopted in this research.

Table 14: Comparison between Questionnaires and Interviews (Gibson and Brown, 2009)

Methods	Questionnaires	Interviews
Types	<ul style="list-style-type: none"> <li>• Self-administrative questionnaires</li> <li>• Questionnaires by post, email, and telephone</li> </ul>	<ul style="list-style-type: none"> <li>• Structured interviews</li> <li>• Semi-structured interviews</li> <li>• Unstructured interviews</li> <li>• Face-to-face interviews</li> <li>• Telephone interviews</li> <li>• Computer interviews</li> <li>• Group interviews</li> </ul>

Advantages	<ul style="list-style-type: none"> <li>• Less expensive than interviews</li> <li>• Large amounts of anonymity</li> </ul>	<ul style="list-style-type: none"> <li>• Appropriate for complex situations</li> <li>• Useful for collecting in-depth information</li> <li>• Supplemented information</li> <li>• Explained questions</li> <li>• Suitable for wider applications</li> <li>• Controlled questions</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>• Low response rates</li> <li>• Self-selecting bias</li> <li>• Unsuitable to all situations</li> </ul>	<ul style="list-style-type: none"> <li>• Expensive and time-consuming</li> <li>• Researcher's bias could be involved</li> </ul>

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### 3.5 Timeline of Research

The researcher was based in China from September 2015 to January 2016, March 2016 to October 2016 and January 2017 to March 2017. The research was comprised of five phases.

- **Phase one** was the literature review phase. The literature review was conducted throughout the whole research period.
- **The second phase** was the case studies. The case study of TZ was conducted from September 2015 to January 2016. Direct observation and document analysis were adopted throughout the case study period. The interviews started in November. Two months were spent becoming familiar with the project and selecting the interviewees. The case study of LX was conducted from March 2016 to July 2016. Direct observation and document analysis were adopted throughout the case study period. The interviews started in April 2016. One month was spent becoming familiar with the project and selecting the interviewees. The results of the case studies of TZ and LX were merged with the findings from the literature review to provide a foundation to develop the interview template for the surveys.
- **The third phase** was the surveys, which lasted from July 2016 to October 2016. The interviews in the surveys were based on the results of the literature review and case studies. The interactions from the surveys provided the fundamental data

for developing an interaction framework.

- **The fourth phase** was the development of a framework, with the interaction framework being developed based on the findings from the surveys.
- **In the fifth phase**, the interaction framework was validated by Chinese experts from January 2017 to March 2017. The resulting revised interaction framework was the final interaction framework.

### **3.6 Adopted Research Methods**

The ethical issues should be considered before collecting data. The research ethical was conducted according to the codes and processes of ethics in university. Additionally, the companies' rules were followed during the case study period. According to the confidentiality agreement, the companies and projects' actual names cannot exist in this research. Their names were replaced by abbreviations. The interviewees' names were confidential and were not presented in this research.

#### **3.6.1 Literature review**

The majority of the literature review is based on articles written in English. However, articles written in Chinese were also consulted when they were specific to the Chinese construction industry and the research objectives. The literature review in this study consists of four important steps, which were discussed in Chapter 2, and are:

- Identifying the definition of construction quality, the current situation regarding construction quality in China and the requirements for improvement in terms of Chinese construction quality through reviewing relevant literature on construction quality in China.
- A historical review of lean construction ideology, which helps the author to understand the definition of lean construction, lean construction development, current lean construction practice, lean construction principles and existing research on using lean construction to improve construction quality. The potential quality-based lean construction theories and potential quality-based lean construction techniques were identified and summarised by reviewing relevant literature about lean construction.
- Using the literature review results to understand the BIM definition, the historical

development of BIM, BIM advantages and existing research on investigating the relationships between BIM and construction quality improvement. Furthermore, quality-based BIM mechanisms and quality-based BIM applications have been identified and summarised.

- Reviewing the current integration studies on lean construction and BIM. Furthermore, important studies, integration trends and existing studies regarding integrating lean construction and BIM to improve construction quality were identified.

The literature review was conducted using a manual review methodology. The literature was obtained from various databases (such as the University of Bath library database, ScienceDirect, Taylor and Francis and the CNKI database) and online resources through search engines (such as Google Scholar). The literature review helps the study to understand the context of the research area in depth and provides a foundation for further research.

### **3.6.2 Case studies**

The researcher spent nine months in China for achieving the research objectives of investigating the quality-based lean construction approaches and the quality-based BIM approaches. Prior to visiting China, the researcher contacted leading construction companies in research topic and asked for permission to collect case study data. In discussions with two large contractors, it was agreed that the author could join the companies as an intern. This allowed the author full access to what the companies were doing, along with access to information that is often difficult to access through other research methods, such as detailed information on projects and working methods.

During this time in China, the researcher had internships with two construction companies in Beijing and was working with future research plans emerging from the literature review. This provided the researcher with a unique insight into the work conducted by Chinese construction companies, which is not often easy for other researchers to achieve.

### **3.6.2.1 Case study intention design**

The findings from the literature review presented:

- Chinese construction quality improvement requirements
- Quality-based lean construction approaches in existing literature
- Quality-based BIM approaches in existing literature

Therefore, the following case studies were designed based on the previous findings from the literature review. The aim of the case studies is to identify more quality-based lean construction approaches and quality-based BIM approaches regarding the Chinese construction industry and investigate the incentives, requirements and limitations of quality-based lean construction approaches and quality-based BIM approaches. This is followed by a feasibility discussion of integrating lean construction and BIM to improve Chinese construction quality.

### **3.6.2.2 Selection criteria for case studies**

As current research on lean construction and BIM is still in its infancy in China, there have not been many practical studies, which has limited the scope for selecting case study companies. The selection criteria set are below:

- Permission to collect case study data
- Implementation experience with lean construction or BIM in regard to improving project quality
- Representative projects have priority

Finally, two large and well-known Chinese construction companies, Company ZJ and HY, were selected through these criteria. One had rich lean construction implementation experience, and the other had applied BIM for many years. Their projects were representative among being built projects in China at that time. As Saunders et al. (2007) state, a single representative case can provide an opportunity to observe and analyse a phenomenon that has not been previously considered. Therefore, it was felt that two case studies were sufficient for this study.

### **3.6.2.3 Data collection techniques**

#### **1) Observation and documentation**

The researcher took part in Project TZ as an intern. The position of the researcher in

the company was the assistant to the construction managers. This position provided many opportunities to observe how the project operated and the detailed application of lean construction. Construction site visits and the observation of meetings were usually used to observe the projects. Questions were raised based on this observation, which were then discussed and answered by the project manager. During the construction period, some interactions between lean construction and construction quality improvement were summarised through close observation. The intuitive and primary information that was obtained from observation was also used as a form of evidence regarding the relationships between lean construction and construction quality improvement. The observations conducted at the BIM-based Project LX were similar to those for the lean construction-based Project TZ. The researcher's position at company HY was also the assistant to the construction manager. Direct observation was adopted to observe the relationship between BIM and construction quality improvement in Project LX.

The documents for Project TZ, including the meeting records, lean construction implementation plans, announcements from the company, administrative documents, implementation procedures and quality defect reports in the construction project, were also regarded as written evidence for identifying quality-based lean construction approaches. Although not all of the relevant company documentation could be acquired as some of it was confidential, it was still useful for providing insights in order to identify quality-based lean construction approaches. The documents gathered for Project LX were analysed in a similar way to Project TZ. The documents provided direct evidence in investigating the relationships between BIM and construction quality improvement.

## **2) Interviews**

In-depth interviews were adopted in this research to invest depth information about quality-based lean construction approaches and quality-based BIM approaches. Some unexpected discoveries were found through in-depth interviews.

### **(1). Interview template design**

There are four topics in the interview template relating for investing quality-based lean construction approach, which were:

- Background information
- Current quality-based lean construction theories
- Current quality-based lean construction techniques
- Incentives, limitations and requirements of using lean construction to improve construction quality

All questions were open-ended. The quality-based lean construction theories and techniques in existing literature (see Table 5 and Table 6) were chosen whether to provide depending on the circumstances during interview. When the interviewee was not clear about the meaning of theories or techniques are, these examples can be presented to facilitate the understanding of the interviewee. Additionally, although there is no necessary to provide an interview schedule of an in-depth interview, the interview schedule was adopted in this research for some particular reasons. Most of the interviewees were managers which were quite busy and it was difficult for them to participant into a long unlimited time interview. Therefore, it was necessary to let them know how long the interview will take, which also made the researcher book an interview time with interviewees easier. The interview template in Project TZ which consists of an interview schedule and interview topics are attached in Appendix 1.

Similarly, to interview template on investigating quality-based BIM approaches, there are four topics in the interview template, which are:

- Background information
- Current quality-based BIM mechanisms
- Current quality-based BIM techniques
- Incentives, limitations and requirements of using BIM to improve construction quality

All questions are open-ended. The interview template in Project LX which consists of an interview schedule and interview questions could be seen in Appendix 2.

## **(2). Interview sampling**

According to Ramsden (2016), the semi-structured interview sample selection is usually based on experience. The samples of the semi-structured interview could be limited by practical limitations such as time limitation and interview number limitation. In this research, the development of lean construction and BIM in China were in their infant stage. Both lean construction and BIM were not widely applied in China which results the suitable potential interviewees were quite limited. It was very difficult to achieve a large interview sample size due to the limited numbers of available interviewees and limited research time. Therefore, all the managers and professionals in Project TZ, whose work were related to lean construction and quality management were selected as interview candidates. The interview sampling principles are:

- Voluntary principle
- Their works are related to lean construction application in case study project
- Choose candidates with longer lean implementation year
- The candidates in higher positions in the company are preferred when they have same lean construction application year

Finally, 15 experts were selected to participate into interview according to their positions in the company and their lean construction and quality management application experience (see Table 17 in Section 4.2.1). Meanwhile, in the Project LX, all the managers and professionals whose work were related to BIM and quality management were selected as interview candidates. There were 16 interviewees were selected based on their positions in company and their BIM and quality management application experience (see Table 20 in Section 4.3.1).

## **(3). Interview process**

### **Making interview strategies**

The aim of the in-depth interviews in this research was to explore in-depth what the interviewees felt about predetermined topics. The interviewees were given time to think about the topics and they were encouraged to explain their thoughts in detail. The interview templates were sent to the interviewees a week before the interviews to



give them enough time to prepare their answers.

In order to get more in-depth information from the discussions, the background understanding of the interviewees' emotions, views and beliefs was necessary. This helped to understand what they said. Additionally, the interviewees were uncertain about some of their answers. This could be identified by focusing on the information given following noises like 'hmm' or 'uh-uh'. The emotions and the body language were also observed in this situation and notes were taken when necessary. Moreover, the assurance of anonymity in the research was given at the beginning of the interview to reassure the interviewees so that they could relax. The conversation was processed in an easy way to encourage the interviewees to reveal their actual feelings about the topics. Furthermore, in some interview situations, the interviewees provide information that they think the interviewer wants out of politeness. In this case, interviewers need to pay attention to their own words and should try to use neutral words without showing emotions. The interviewees also need to be encouraged to give their true feelings.

Interviewees also need to be encouraged to talk continuously. The interviewer should reassure the interviewees that their views are appreciated. Additionally, the location of the interview should make the interviewee comfortable. All of the interviews in this research were conducted in company meeting rooms as a place that the interviewees were familiar and comfortable with. Another reason for choosing the meeting rooms was to eliminate the influence of noise. Furthermore, one-to-one interviews were conducted in this research. Having another person present could have made the interviewees shy and unable to express their views well. Overall, the interviewer's general responsibilities in interviews are conducting the interview, guiding the discussion in the right direction, investigating the topic in depth and encouraging the interviewees to cooperate and give their real feelings.

### **Running a pilot study**

A pilot study is vital in the interview process. It allows the researcher to spot the flaws in their research questions before the actual interviews (Evans, 2007). Running a pilot

study in this research allowed the researcher to understand the research questions well and to become familiar with the interview timeframe. The pilot studies were conducted with six colleagues in Project TZ and five colleagues in Project LX. The pilot studies went well and no interview topics needed to be revised. Additionally, the skills of making notes and recording the interviews were practised in the pilot studies.

### **Capturing the interview data**

Note-taking is usually adopted during interviews. In this research, notes were used to mark the important information in the interview. These notes were checked immediately when the transcripts were made while the interviews were still fresh in the mind.

Voice recording was adopted in the interviews with the permission of the interviewees. The interviews were recorded using voice recording software in an iPhone. The recordings were helpful as the researcher could concentrate on controlling the interviews and could listen to the details after the interviews.

According to Patton (2001), the transcription process helps in understanding the collected data. Therefore, the recordings were manually transcribed verbatim. Additionally, the recordings were listened to more than once to make sure that all of the useful information was transcribed. Any of the statements related to a specific theme were marked out so that they could be found easily later.

### **(4). Interview data analysis**

According to Tesch (1990), there were six basic principles adopted to analysis qualitative data. These principles are briefly described in the followings.

#### **Interview data analysis principles**

##### **Systematic analysis**

The analysis of the collected data should proceed in an orderly manner. The analysis approach should be carefully organised and the work should be documented along with the analysis process.

### Producing tracking notes

As analysing interview results is a sophisticated process which cannot be finished in a short time, tracking notes were adopted in this research to mark out the important information and to aid the ongoing works.

### Segmenting the data

The interview results were too long and it was necessary to break them down into several meaningful segments. The information contained in each segment reflected the same theme.

### Categorising the segments

The segments were categorised so that they could be arranged systematically. The categories were identified from the collected interview data.

### Flexible categories

The categories were continually updated throughout the interview data analysis process. The categories were flexible so that they could be revised and restructured.

### Taking care of synthesis

Categorising the segments was undertaken to facilitate an understanding of the collected data. The result of the data analysis allowed for the segments to be synthesised to reflect the overall understanding of the data. The overall picture of the data is important.

### **Practices of data analysis**

A thematic analysis framework was selected to analyse the interview data from the case study. This analysis approach is simple and convenient for new researchers who are unfamiliar with controlling complex types of qualitative data. The detailed and comprehensive description of the data could be achieved by adopting a thematic analysis framework. This was completed through the following steps.

#### Familiarising oneself with the collected data

All of the data should be reviewed with two questions in mind: ‘do the results reflect the research questions?’ and ‘why they respond in this way?’ The transcripts were read according to the interview data analysis principles discussed below. During this stage, some notes were made to highlight the important information.

#### Generating initial codes

The codes could be identified manually or by using software, such as NVivo. The manual approach was selected in this research. Highlighters, pens and Post-it Notes were used to provide analysis notes. The important words in the transcripts were highlighted and translated into codes. It was important to identify as many potential codes as possible. Data that was identified as having the same code was collated.

#### Searching for themes

This step focused on the broader level of themes and involved sorting the different codes into potential themes. Mind maps were adopted to help discover the themes. A3 paper was used to write down the codes and then to analyse them and form themes. These papers were posted on the wall together to provide an overall insight into the themes.

#### Reviewing the themes

The themes were reviewed again in this step and some themes were transferred into other themes or some themes were deleted as they overlapped with others. The coded data was reviewed to make sure that all of the codes were properly separated into themes. Then, the themes and the relationships between the themes were reviewed.

#### Defining and naming the themes

The themes were named in this step. The names were concise and clear so that readers would know what they are.

#### **Interview validity**

The interviews were based on subjective, interpretive and contextual data. The validity

of the interview results should be considered. According to Maxwell (1992), the four approaches to judging the validity of interview results are descriptive validity, interpretive validity, theoretical validity and generalisability. These questions were asked by researcher to ensure the validity of the interview results in this research.

#### Descriptive validity

Descriptive validity is the judgment of the accuracy of the data (Maxwell, 1992). The accuracy of the data in this research was checked by making sure no data was omitted and there were no transcriptional errors. Verbatim interview transcripts were generated to ensure that all of the recorded data was transcribed correctly. Moreover, the interviewees' stresses, pitches and noises like 'hmm' or 'uh-uh' were focused on to ensure the accuracy of the data.

#### Interpretive validity

Interpretive validity refers to the assessment of the validity of conclusions generated by the researcher (Punch, 2005). The interviewees' answers were separated into different categories according to the researcher's understanding of the interview results. It was necessary to establish a close link between the researcher's understanding and the actual meanings of the interviewees. The processes of drawing conclusions and forming categories were supported by two PhD students and three master's students. The difficulties in understanding the meanings of the interviewees were dealt with using group discussions.

#### Theoretical validity

As Maxwell (1992) states, theoretical validity is adopted to address the theoretical constructions of research. In order to achieve theoretical validity, an overall picture of the data based on the research aim and objectives always existed in the researcher's mind. Periodic summaries were adopted to provide an overall view of the collected data and to sort the data into categories. The categorised segments were synthesised at the end of the research.

#### Generalisability

Generalisability is concerned to apply the result to universal (Maxwell, 1992). In order to make the interview results transferable to similar projects, the case study projects and interviewees were carefully selected. The projects were representative of the research area in China. Project TZ adopted many quality-based lean construction approaches and a number of quality-based BIM approaches were recognised in Project LX. The contractors for these projects had lots of experience applying either lean construction or BIM techniques. The interviewees were also carefully selected according to their positions in the companies and their experience with either lean construction or BIM. Therefore, the risk of the lack of generalisability was reduced. Additionally, the whole process of the interviews in the case studies can be illustrated in a flow chart (see Figure 4).

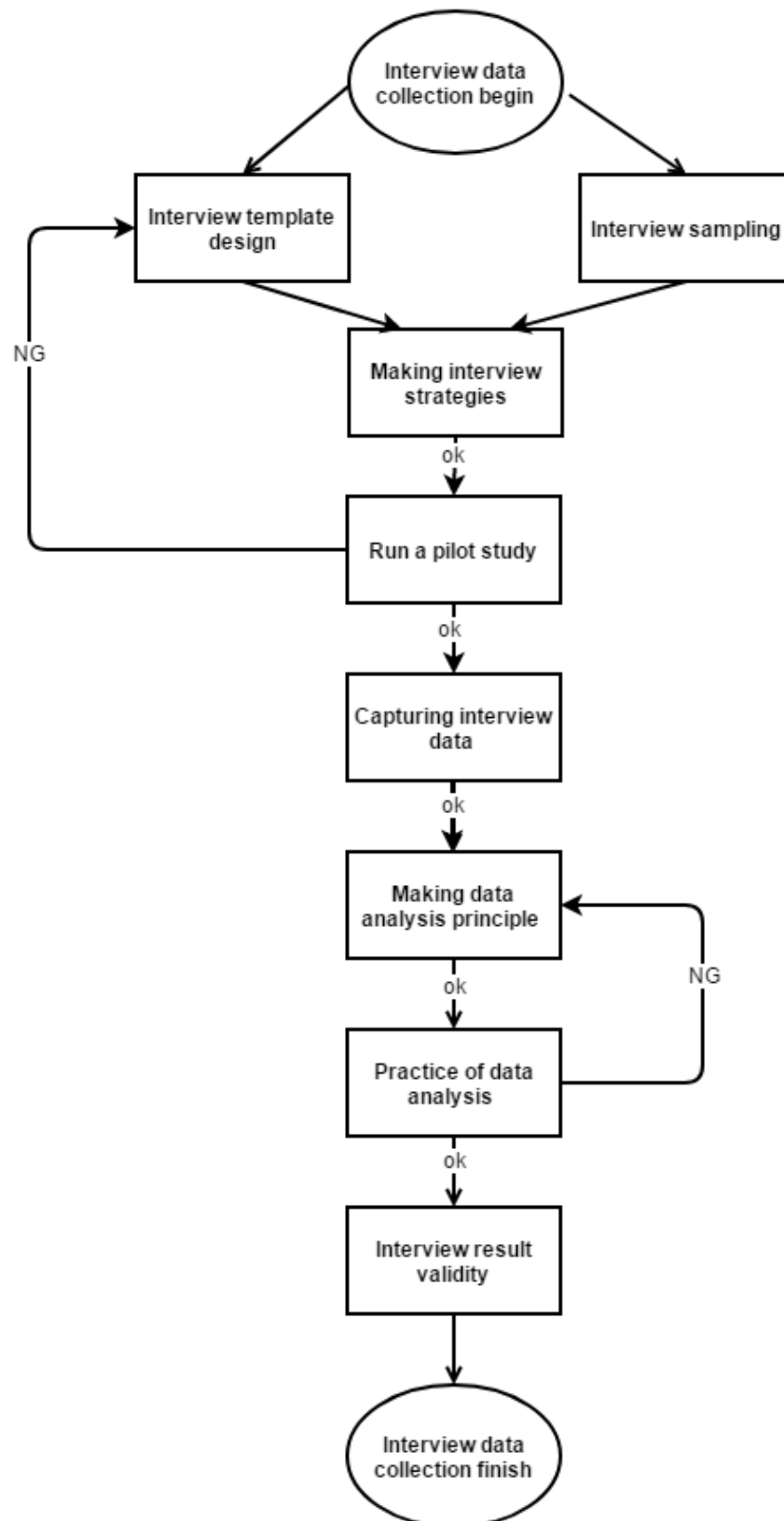


Figure 4: Interview Process Flow Chart

### **3.6.3 Survey**

The survey research was conducted based on the results of the case studies and literature. The quality-based lean construction approaches and quality-based BIM approaches were identified from the case studies and literature review. The interviews with industry experts in China were expected to reveal the interactions between quality-based lean construction approaches and quality-based BIM approaches.

#### **3.6.3.1 Interview intention design**

The findings from the literature review and case studies indicated:

- Current Chinese construction quality improvement requirements
- Quality-based lean construction approaches
- The incentives, requirements and limitations of quality-based lean construction approaches
- Quality-based BIM approaches
- The incentives, requirements and limitations of quality-based BIM approaches
- It is feasible to integrate lean construction and BIM to improve construction quality.

Therefore, follow-up semi-structured interviews were designed based on previous findings from the literature review and case studies. The aim of these interviews was to confirm the importance of integrating lean construction and BIM to improve construction quality and investigate the interactions between quality-based lean construction approaches and quality-based BIM approaches. The quality-based lean construction and BIM interaction framework were developed based on the results of the interview.

#### **3.6.3.2 Interview template design**

There are four topics in the interview template, which are:

- Background information
- The importance of integrating lean construction and BIM to improve construction quality
- The strategic interactions of lean construction theory and BIM mechanism on



construction quality

- The implementation interactions of lean construction technique and BIM application on construction quality

All topics were open-ended. The interview template consists of an interview schedule and interview questions (see Appendix 3). The reason of including interview schedule was discussed in temple design in case study.

### **3.6.3.3 Interview sampling**

The situation of interview sampling in case study was met again in survey. The limitation of a number of potential interviewees and time-limited the interview sample size. Moreover, the interviewees were expected to have rich experience in construction quality management and understand lean construction and BIM. The sample selection criteria were set as below:

- Voluntary principle: experts were interested in participating in an interview
- Experience principle: experts with lean, BIM and quality management implementation experience are firstly preferred, followed by respondents with BIM and quality management implementation experience who understand lean construction or respondents with lean construction and quality management implementation experience who understand BIM

In addition to being screened by sample selection criteria, the theory of saturation was adopted to propose a reasonable sample size. According to Glaser and Strauss (1967), ‘Saturation is the point at which, after a number of interviews has been performed, it is unlikely that performing further interviews will reveal new information that hasn’t already emerged in a previous interview.’ In this research, the saturation point was 22. Therefore, there were 22 industry experts participated in the interview (see Table 15). These experts came from 16 different construction companies. The background information about these respondents was found through case studies, LinkedIn, academic conferences and recommendations from other.

Table 15: Interviewees in Survey

Name	Designation	Construction Experience (years)	Company Type
1	Project Manager	More than 10	Contractor
2	Project Manager	More than 15	Contractor
3	Deputy Project Manager	More than 10	Developer
4	Deputy Project manager	More than 10	Contractor
5	Technical Director	More than 10	Contractor
6	Construction Consulter	More than 5	Consulter
7	Deputy Project Manager	More than 5	Contractor
8	Deputy Project Manager	More than 15	Developer
9	Technical Director	More than 15	Developer
10	Board of Director	More than 10	Contractor
11	Technical Director	More than 10	Developer
12	Project Manager	More than 25	Contractor
13	Vice-technical Director	More than 20	Contractor
14	Project Manager	More than 25	Contractor
15	Construction Consulter	More than 10	Consulter
16	Technical Director	More than 15	Contractor
17	Project Manager	More than 15	Developer
18	Technical Director	More than 5	Developer
19	Vice-technical Director	More than 10	Contractor
20	Technical Director	More than 15	Contractor
21	Project Manager	More than 15	Developer
22	Vice-technical Director	More than 10	Contractor

### 3.6.3.4 Interview process

The interview process for the surveys was similar to that for the case studies. The details that are repetitions of the information given for the interview process in the case studies are not discussed in this section.

The potential interviewees were contacted to find out if they were available for interviews. The participants were sent the interview schedule and the interview questions one week before the actual interviews. Some of the interviewees worked in Beijing and some were from other cities in China, such as Shanghai, Guangzhou and Wuhan. However, all of the interviews were conducted in Beijing and were audio recorded with the permission of the interviewees. The interviews were comprised of a series of discussions with the interviewees over a period of time. Some of the interviewees were interviewed several times to gain a greater understanding of the issues being investigated while some were only available for one interview. Moreover,

the locations of the interviews were based on the preferences of the interviewees. Cafes, restaurants, libraries, the interviewees' offices and meeting rooms were selected to conduct the interviews.

In order to ensure interview fluidity and rationality, a pilot study was adopted. The pilot study was conducted with the help of five colleagues at Project LX. The pilot study was used to test the interview topics and assess the timeframe of the interviews. The pilot study went well, so the interview topics were not revised. In general, all of the interviews were finished within a three-month timeframe.

#### **3.6.3.5 Interview data analysis**

The interview data analysis method for the surveys was the same as for the case studies. Thematic analysis was adopted to analyse the interview data from the surveys. Therefore, a detailed discussion is not provided in this section to avoid repetition. The interview data is analysed in detail in Chapter 6.

The threshold of acceptance for the surveys was 50%, which meant that the selected interactions were accepted by more than 11 participants from total 22 participants. Additionally, the interaction which its agreement between 50%-60% should be reconsidered its valuable. The interactions that were agreed with by more than 50% of the participants but disagreed with by some of the participants needed to be discussed again.

#### **3.6.4 Framework development**

Once the interview data had been collected and analysed, the next step was to develop the framework. A two-level quality-based lean construction and BIM interaction framework were developed based on the key findings from the interview in survey. Moreover, the framework was developed based on the research of Sacks et al. (2010).

Sacks et al. (2010) investigated the interaction between lean construction and BIM and developed an interaction framework to present their relationships in detail. This framework is quite illuminating. A matrix is used to juxtapose BIM functionalities with

prescriptive lean construction principles. The framework is concise, and the interactions between lean construction and BIM are presented in a bare matrix. This is helpful for researchers to recognise the potential synergies in this framework. Therefore, this research was inspired by the framework from Sacks et al. and developed a framework according to the findings from the survey.

The quality-based lean construction and BIM interaction framework consist two levels, which are the strategic level and implementation level. The strategic level framework aims to present the interactions between quality-based lean construction theories and quality-based BIM mechanisms. The implementation level framework aims to present the interactions between quality-based lean construction techniques and quality-based BIM applications. Detailed discussion on this framework can be found in Chapter 6.

### **3.6.5 Framework validation**

According to the limited experts on lean construction and BIM in China, it was impossible to adopt questionnaires to validate the framework which needed a large number of responders. The validation process aimed to get experts' comments and achieve recommendations for revising framework. Therefore, the research was apt to in-depth interview due to it was an efficient way to get in-depth insights of interviewees.

#### **3.6.5.1 Validation design**

Validation is the scientific inquiry of real-world comments in a framework (Pidd, 2009). According to Patton (2002), the accuracy and degree of completion of the research outcome are detected through validation process. In this research, validation has been adopted to check the accuracy and degree of completion of the quality-based lean construction and BIM interaction framework.

#### **3.6.5.2 Validation interview template design**

There were five topics in the validation interview template, which were:

- Strategic level interaction framework structure validation
- Strategic level interaction framework content validation

- Implementation level interaction framework structure validation
- Implementation level interaction framework content validation
- Further recommendations

All topics were open-ended. The validation interview template was attached in Appendix 4.

#### **3.6.5.3 Validation sampling**

The situation of interview sampling in case study and survey were met again in the validation phase. The solution was the same. The interviewees were selected from the remaining candidates in candidate pool in the survey (interview) stage. There were ten interviewees who agreed to be involved in the research. All of the interviewees had more than ten years of experience in construction quality management. Furthermore, these interviewees had at least lean implementation experience or BIM implementation experience, and some have both lean and BIM implementation experience.

#### **3.6.5.4 Validation interview process**

The validation interview process was similar to it in the case study and survey. The unnecessary details which repeat with the interview process discussion in case will not be discussed in this part.

The interview template which contains research topics and research schedule, and the two-level quality-based lean construction and BIM interaction framework were sent to interviewees one week before interview began. According to the interview location put forward by the respondents, the interviews were conducted in cafés, meeting rooms in library and their offices. Additionally, eight of the interviews were face-to-face while two were conducted over the telephone.

#### **3.6.5.5 Interview data analysis**

The analysis process of validation interview data was thematic analysis which was similar with previous analysis process in case study and survey. Therefore, the detail discussion will not be provided in this section to avoid repetition. Additionally, a

detailed discussion regarding the interview data analysis can also be seen in Chapter 6.

## **Chapter 4: Case Study Results**

### **4.1 Introduction**

This chapter discusses the case study findings to achieve the research objectives of summarising and examining the potential use of lean construction and BIM to improve construction quality. Two construction projects are involved as case studies. One has been chosen as a lean construction case study, while the other has been chosen as a BIM case study. Both of the companies are based in China. The case study findings are based on observations, a number of face-to-face interviews and site documents.

A background discussion is the first part of each case study. The quality-based lean construction approaches and quality-based BIM approaches that have been adopted in the projects are identified and discussed. The case studies focus on four main aspects, two for quality-based lean construction theories and two for quality-based lean construction techniques, which have been identified in the literature review as the following:

#### **Potential use of lean construction to improve construction quality**

- Quality-based lean construction theories
- Quality-based lean construction techniques

#### **Potential use of BIM to improve construction quality**

- Quality-based BIM mechanisms
- Quality-based BIM applications

This chapter is crucial for the formation of an interaction framework. New knowledge about quality-based lean construction approaches and quality-based BIM approaches can be obtained through case analysis, and some approaches presented in the literature review can be verified. As the collected data is qualitative, it can help to understand the opinions of the interviewees.

Due to the requirements of confidentiality, the project names, the developers' names and the names of the contractors mentioned below are replaced by letters.

## **4.2 Case Study Findings for Project TZ**

### **4.2.1 The background of the project**

The TZ Project was located in the southeast of Mentougou District in Beijing. The project related to constructing a high-rise building. The project area was originally a small village, and basic demolition was completed before the project began. There was no underground pipeline distribution at the site, and the west and north sides of the site were planned roads. The building adopted a frame-shear wall structure, which reached 7 degree aseismic in China's intensity scale. The total construction area was about 42,000 m<sup>2</sup>. There were 21 levels over ground and one level underground. The total height was about 91.5m.

The project was built by ZJ Company. ZJ Company is a large comprehensive construction group with the ability to build projects related to civil and industrial construction, municipal engineering and smelting engineering. ZJ has many years of experience in lean construction implementation and training. For many years, ZJ Company has been cooperating with the American LCI. A group of experienced on-site managers who are familiar with the application of lean construction work at ZJ Company,

The quality objective of the project was to win 'Great Wall Cup' quality award if possible. It was also one of the key projects of the company. A quality management group was composed of the construction company, a project management team of developers, a design company and a supervision company. ZJ Company carries out specific construction and quality control work for all projects. The detail interviewees' information is listed in Table 16. There were 15 interviewees participated in in-depth interviews. All of them had construction experience more than five years (see Table 17).



Table 16: List of the Interviewees for Company ZJ

<b>Name</b>	<b>Designation</b>	<b>Construction experience (years)</b>
1	Board of Director	More than 20
2	Project Manager	More than 15
3	Deputy Project Manager	More than 15
4	Deputy Project Manager	More than 15
5	Technical Director	More than 10
6	Construction Technologist	More than 5
7	Deputy Project Manager	More than 10
8	Lean Construction Technologist	More than 5
9	Vice-technical Director	More than 15
10	Lean Consulter	More than 10
11	Construction Technologist	More than 10
12	Lean Construction Technologist	More than 5
13	Vice-technical Director	More than 20
14	Lean Construction Manager	More than 15
15	Vice-technical Director	More than 15

#### 4.2.2 Quality-based lean construction theories and techniques

The quality-based lean construction approaches used in Project TZ are identified in this section. Specifically, the quality-based lean construction theories and quality-based lean construction techniques for this project are summarised in Table 17 and Table 18, respectively. Further detailed evidence in the form of qualitative data is provided and discussed below.

Table 17: Quality-based Lean Construction Theories Identified in Project TZ

<b>No.</b>	<b>Quality-based lean construction theories</b>
1	Conversion to a quality-based mindset
2	Decentralised control- giving authority to worker
3	Pull-based quality management
4	Cooperation and communication

Table 18: Quality-based Lean Construction Techniques Identified in Project TZ

<b>No.</b>	<b>Quality-based lean construction techniques</b>
1	Last planner system
2	5S management
3	Kanban
4	Standardisation

#### **4.2.2.1 Potential quality-based lean construction theories**

##### **(1) Conversion to a quality-based mindset**

The first quality-based lean construction theory used in the project was identified as the conversion to a quality-based mindset. According to Interviewee 1:

[...] Each individual on construction sites has different responsibilities in terms of quality control and everyone's behaviour will affect the quality of the final building outcomes. Therefore, only through mobilising each participant's enthusiasm for quality control and letting every participant concern about construction quality can finally delivery construction products to meet or exceed the customers' expectations [...] - Interviewee 1

The Interviewee 2 also mentioned that quality could be improved through a mindset conversion, which was showed in the following quote:

[...] Managers have the responsibility to promote quality-based mindset conversion. Managers should make the quality responsibilities of each department clear after the quality policy and objectives have been are determined. Then, the sub-managers in each department should continue to break down the quality responsibilities to each worker. Therefore, everyone knows their role and responsibilities in terms of quality control [...] - Interviewee 2

Through the interviews in Project TZ, some of the managers in Company ZJ were familiar with Crosby's Zero defects theory. However, they had their explanations of this theory. According to Interviewee 5:

[...] 'Zero Defects' does not mean the final products need to be perfect but to let the construction process be perfect. Some managers in other companies may believe the zero defects means product perfect which is required by using

better quality materials, more supervision teams and large amounts of inventory to meet the demand. This kind of 'Zero Defects' causes resources waste and construction production usually does not make customers satisfied due to the project may exceed the cost or time schedule. Sometimes, according to the finance and construction time constrains or design intentions, it is impossible or no necessary to have a perfect final production. However, it is possible to conduct perfectly in the construction process. The best quality under such conditions could be achieved in the construction process by adopting the appropriate management and techniques [...] - Interviewee 5

Quality, as the result of the conversion to a quality-based mindset, were improved naturally. The managers in ZJ Company not only required staffs to change their mindsets but it also proposed a new quality spirit, evidenced in the following quote:

[...] We require every member of staff in the company to shift their mindset to a quality-based mindset. Quality is the top priority in the construction process. In order to facilitate everyone to recognise the importance of quality, we put forward the quality spirit of 3N, which is 'Not to build substandard construction products', 'Not to accept substandard construction products' and 'Not to deliver substandard construction products'. The 3N spirit reflects an attitude to quality defects. [...] - Interviewee 4

As Interviewee 4 further added, since the beginning of the activities to change mindsets to quality, the quality of the construction had been gradually improving at the company.

## **(2) Decentralised control -giving authority to the workers**

It can be identified that the quality-based lean construction theory of decentralised control was used in Project TZ. According to Interviewees 2 and 3, workers are well suited to be assigned the task of identifying quality defects by themselves. This requires the workers in adjacent construction stages to check each other. Interviewee 3 elaborated more on decentralised control. In Project TZ, the inspection authority was handed over to the workers. The workers were the inspectors of the workers in the

previous construction stage. Workers were responsible for checking the quality of preceding work and conducting self-checks. The quality of all work was inspected by workers in the next stage. The workers for each process were both their own process inspectors and inspectors of the previous process. Decentralised control was mentioned to its important by Interviewee 1, as evidenced in the following quote:

[...] The managers could emancipate themselves from trivial quality management activities to focus on more important management and plan work by transferring part of the quality management work to the workers. According to our experience, since the quality control authority is transferred to the workers, the managers find that the defects are detected earlier by workers' observations and corrected at a lower cost than before [...] - Interviewee 1

According to Interviewees 2 and 15, the benefits of workers having authority over construction quality control is recognised by managers. Interviewee 15 further supported his argument:

[...] We encourage workers to offer suggestions on construction plans and construction quality plans. The work plan is made by managers and workers. The workers need to check all required conditions for construction before they sign the plan. Sometimes, workers know more about the conditions for the commencement of construction than we do. The workers' opinions can supplement the deficiencies of our plan, which prevents unreasonable plans from being generated. [...] - Interviewee 15

### **(3) Pull-based quality management**

According to the observation of Project TZ for this study, pull-based quality management is similar to the lean theory of giving authority to the workers. One difference between them is that pull-based quality management emphasises pulling quality by the workers in the next construction stage. When discussing pull-based quality management, Interviewee 14 confirmed that there are two kinds of customers

in the construction quality management system of ZJ Company, which are the immediate and the end-user customers. Interviewees 3 and 14 further explained that each worker in the next stage is the immediate customer for the workers in the current stage, and the owner of the project and the government are the end-user customers for the whole project. The owner and the government provide general quality requirements, which are broken down into smaller requirements for each construction stage. According to the observation results, the workers within Project TZ combined the end-user customers' quality requirements and the conditions of the actual needs in each construction stage to identify the quality requirements for previous construction processes. The quality requirements were all pulled up through each process from the workers from the next stage. All on-site workers were responsible for meeting the requirements of both the immediate and the end-user customers.

#### **(4) Cooperation and communication**

The quality-based lean construction theory of cooperation and communication was not formally proposed in the company document for Project TZ. However, according to Interviewees 3, 5 and 6, the importance of cooperation and communication was realised, as evidenced in the following quote:

[...] Due to the increasing complexity of the project, various construction participants were involved in the project. The quality of the project can be influenced by different participants from different aspects, which leads to cooperation is imperative. From a company standpoint, mutual benefit and win-win results are what we want to see. Our cooperation is open and transparent and is aimed at the mutual benefit and common development. The behaviour of optimising our own benefits at the expense of others cannot last long. We should actively cooperate with other participants to meet the expectations of the customers for quality [...] - Interviewee 5

Interviewee 6 further added that regular meetings were organised online. Owners, designers, contractors, suppliers, supervisors and other participants gathered together to share their information of the current construction quality, schedule and cost, as well

as to communicate and resolve the difficulties of the project. Effective communication was used to avoid misunderstandings between the different participants of Project TZ.

It can be concluded that cooperation and communication is an approach that cannot be ignored in improving construction quality, even if it is not formally proposed in company documents. A company's quality management is carried out in accordance with the theory of cooperation and communication. So it just has not been summed up at the theoretical level.

#### **4.2.2.2 Potential quality-based lean construction techniques**

##### **(1) Last planner system**

According to Interviewee 10, the LPS was applied in the project, which was influenced by the lean theory of decentralised control. Almost all of the interviewees confirmed that LPS was a highlighted technique of the company in improving construction quality in terms of planning rationality. Therefore, the role of LPS in quality improvement is undoubted. From ZJ Company's experience of implementing the LPS for many years, the rationality of its plans has been improved after last planners are involved. The improvement of plan rationality further affects the quality of the construction process.

There are five important steps to the LPS, as listed by Interviewee 4, which are the following:

- The master plan
- The phase plan
- The look-ahead plan
- The weekly work plan
- The percent plan complete

Interviewees 3 and 10 further discussed how these five steps improved the plan quality in this project. The master plan was not a detailed plan as it was used to explain general construction strategies and set milestones for the target start and end dates. It is

important to note that this plan needed to be closely linked with the expectations of the customers. The customer requirements were important references for making the master plan. Therefore, a customer-based master plan was a good start to steering the whole plan to success. Compared to the master plan, the phase plan was more detailed. It divided the master plan into many phases and gave clear targets for each phase. The responsibilities were clear for each participant in this plan.

Interviewees 9 and 11 both stressed the importance of the look-ahead plan and the weekly work plan in the LPS. The look-ahead plan was adopted to eliminate all predictable construction constraints, which included human resource, material and technical constraints. All of the potential constraints were discussed in advance before the actual construction began. All potential alternative plans were analysed and verified at this stage. The foreseeable limitations of the plans were discussed and resolved. However, as projects progress, there are always some unpredictable conditions experienced on construction sites. Construction plans need to be updated according to these conditions. The workers, as last planners, were encouraged to participate in the weekly work planning and to provide suggestions for the plan. The experience gained from the construction process made the plan more efficient and reasonable. Last planners were invited to attend meetings to discuss the plan for the next week every Monday morning. As the last planners were involved, the plan kept pace with the construction process as it was updated in a timely manner according to the current on-site construction status.

The last planning step that was mentioned by Interviewees 4 and 13 was the percent plan complete (PPC). This step was used to measure the percentage of construction work complete and to analyse the reasons for works being incomplete. This was an important step in the continuous improvement of the plans. The PPC relied on monitoring the weekly work plan and detecting the percentage of the completion of promised work. Similar problems could be avoided in future work after tracking the reasons that works were not completed on time.

## **(2) 5S management**

When the observation of Project TZ began, 5S management had not yet been carried out. At first, the managers were not concerned about 5S management. As the project progressed, some quality defects caused by the disordered nature of the construction site began to appear. After investigation, the experts in the project decided to use 5S management to solve the problems. The role of 5S management soon became obvious . According to Interviewee 7, the effect of 5S management on quality management was underestimated at first, as evidenced in the following statement:

[...] Essentially, 5S management is similar to civilised construction in conventional project management. The control of construction environmental factors is most easily overlooked in the process of quality management. That is why 5S management was underestimated at the beginning of the project [...]  
- Interviewee 7

According to Interviewee 6, the five principles of sorting, simplifying, sweeping, standardising and self-discipline are necessary for improving construction quality. Implementing 5S management can help arrange the layout of a construction site reasonably and can purify the working environment. Working efficiency and construction quality can be improved by making construction sites neat and orderly. After reading through the documents within ZJ Company about 5S management, the quality functions of the five principles are understood as follows:

- The first S (sorting) means collecting all construction tools and materials according to the category. Sorting each work area via a reasonable construction site layout and tidying up work areas can improve the construction site situation.
- The second S (simplifying) means to simplify the construction site and distinguish between the necessary and unnecessary items on-site. Only the necessary items should be kept. Then, the necessary items should be put in the right place.
- The third S (sweeping) means physically cleaning the construction site. Sweeping establishes a good construction environment by keeping the construction site clean.
- The fourth S (standardising) means creating a standard way to monitor and maintain the first three ‘S’ principles of sorting, simplifying and sweeping. The



workers should understand how to conduct standard work.

- The fifth S (self-discipline) means maintaining 5S agreements and deepening the awareness of 5S philosophy. It mainly refers to improving the 5S consciousness of the workers.

Based on observations of the project, the construction site was chaotic before applying 5S management. Construction tools were placed at will. Materials were stacked in a disordered manner. Construction waste, such as construction residue, as well as paper scraps and cigarette butts were not cleaned up. This situation changed after 5S management techniques were adopted. The implementation of 5S management started with the establishment of temporary storage areas for various building materials. Materials were not permitted to be stored outside the temporary storage area. Furthermore, multiple placement points for construction tools were set up. The workers left tools at the placement points according to category when they left the construction site. Everyone had to clean up their own construction areas and take unused items away from the site to keep it clean and tidy. A standardised construction site template was provided for the staff by establishing a demonstration area. The quality defects caused by the construction environment did not appear again.

### **(3) Kanban**

The kanban technique was used in Project TZ as an approach to transferring information. The workers could clearly understand the number of materials, specifications, construction time, construction standards and construction locations before actual construction began by implementing the kanban technique, which effectively ensured construction product quality and avoided over-production and unnecessary tasks being undertaken. According to Interviewees 2 and 5, kanban could facilitate the standardisation of on-site material processing and distribution. The standardisation of construction was also improved by kanban. The quality of construction could be better controlled through kanban-based site management. For the company, kanban was a promising technique for improving quality.

Referring to the company's kanban experience, Interviewee 4 further explained its

application through construction information boards, quality acceptance boards and rework tracking boards:

[...] There are four kinds of boards in the company's Kanban system. They are material boards, construction information boards, quality acceptance boards and rework tracking boards. The material for Kanban is plastic. Kanban is divided into four different colours due to different application purposes. We usually recommend adopting the Kanban technique with LPS together to achieve more benefit in terms of the quality aspect [...] - Interviewee 4

According to the descriptions within company documents, the material boards contained the specifications, quantities and types of the required materials. Furthermore, details of the construction tasks were specified on the construction information boards. The quality acceptance boards provided the information of the quality inspection standards for the construction tasks. The rework tracking boards usually contained information of inspection times, quality defect descriptions, quality defect locations, the person responsible for the defect and the schedule for rectification.

Interviewees 4 and 5 described the benefits of kanban from a quality improvement perspective. The material processing personnel carried out processing work according to the information on the material boards. Processing defects due to unclear information did not occur in the material processing process. Every worker's tasks and responsibilities were made clear by the information on the construction information boards, which helped the workers to complete their work efficiently. The quality acceptance boards provided information on inspection standards. The workers should have had the standards in mind during construction and strictly followed the operating procedures and quality specifications so that the quality of the construction products could meet the required standards. The rework tracking boards were used to supervise and support the construction modification work, with the aim to modify the defects at the minimum cost.

#### **(4) Standardisation**

According to Interviewee 2, the construction process contains many repetitive construction activities, and the quality of those activities can be gradually improved by establishing standard construction procedures. Standardisation can be implemented according to the principle of continuous improvement, and the standard procedure can be updated when better approaches emerge. As Interviewee 2 further stated, refining construction techniques and work procedures are necessary for standardisation. Each construction procedure within ZJ Company was refined into operating standards according to the construction experience of the company and the results of the expert analysis. Then, the scientificity and rationality of these operating standards were verified by the actual operations of the company's construction team. A standardised operating manual was formed by connecting the operating standards. Additionally, some physical models demonstrating standard construction products were also adopted in the project, providing an intuitive approach to understanding standardisation.

#### **(5) First run study**

A first-run study was not implemented in Project TZ. However, when referring to quality-based lean construction techniques, Interviewee 7 directly discussed first-run studies. Although a first-run study was not used in this project, this interviewee had experience applying first-run studies to improve quality in other projects. As he mentioned, a first-run study is used to help managers identify several alternative plans and choose the most suitable plan among the possible options. Videos, photographs and graphics are frequently adopted in first-run studies to describe the alternative options in detail. Interviewee 7 further added that first-run studies help managers make reasonable decisions according to actual construction site conditions. First-run studies are essential for unfamiliar tasks in which the managers lack experience. A first-run study is also helpful for proceeding with construction standardisation and fulfilling quality requirements.

#### **4.2.3 Incentives, limitations and requirements of quality-based lean construction**

Before the arrival of the author, the ZJ Company lacked deep thinking about incentives, limitations and requirements of quality-based lean construction. However, experts had

analysed the incentives, limitations and requirements of implementing lean construction to improving construction quality from the perspective of meeting the quality improvement requirements.

#### **4.2.3.1 Incentives of quality-based lean construction approaches**

Although ZJ Company did not implement the quality-based lean construction theory of 'proactive quality defect prevention culture', the interviewees still confirmed the quality-based lean construction theory of proactive prevention. According to Interviewee 4, proactive prevention of quality defect is the primary requirement of quality management in China, which coincides with quality-based lean construction theories, as evidenced in the following statement:

[...] According to quality-based lean construction theories, inspection-based conventional quality control does not conform to the current quality requirements. Prevention-based proactive quality management, as a foundation of lean quality management, should be continuously pursued by companies in China. Lean construction efforts to actively transform participants' quality thinking into proactive quality management. The quality improvement requirements of proactive prevention can be achieved via a quality-based lean construction approach [...] - Interviewee 4

As required by Chinese construction quality improvement requirements, future quality management in the construction industry in China should result in participants correcting their attitudes on quality and there is no bottom line for quality defects allowed in quality management. The people involved in a project are responsible for pursuing zero defects and do the right thing at the first time. As Interviewee 6 stated, lean construction could fulfil the requirement of quality.

[...] Lean construction quality management pursues construction at the right quality level, at the right time and without waste. In lean construction theories, it is believed that any management cultures that allow for quality defects are bound to fail. The conversion to a quality-based mindset is emphasised in lean

theories to encourage workers to uphold quality at all times. The quality improvement requirements of a quality-oriented mindset and the lean construction theory of conversion to a quality-based mindset are met when managers implement quality management [...] - Interviewee 6

Cooperation was one of the most important quality-based lean construction theories even though it was not formally proposed in ZJ Company. ‘Win-win cooperation’ is required in Chinese construction quality improvement. This is also the theory which the company was carried out. The lean theory of ‘cooperation and communication’ overlaps with Chinese construction quality improvement requirements. According to Interview 1, the importance of cooperation on improving quality was realised as evidenced in the following.

[...] Cooperation is advocated in lean construction and information should be shared between participants. The quality improvement requirement of effective cooperation can be achieved through lean construction [...] - Interviewee 6

Continuous improvement through standardisation is required for quality improvement. This is reflected in two aspects of lean construction: continuous quality improvement and standardisation. The continuous improvement is mentioned important by Interviewee 1 as evidenced in the following:

[...] Although it is hard to achieve perfection, the goal of perfection should be pursued perpetually [...] - Interviewee 1

The theory of continuous improvement should be applied to every aspect of a project, as should standardisation. A standard work process is required in lean construction. This opinion was supported by Interviewee 7, as evidenced by the following statement:

[...] Standardisation should be implemented according to the principle of continuous improvement. For this aspect, lean construction can fulfil the

requirements of quality improvement [...] - Interviewee 7

Customer requirements should be the focus of quality management. Customer requirements are the most important consideration in defining quality. Quality goals should not only conform to national construction laws and technical specifications but should also fulfil customers' requirements. As Interviewee 11 stated:

[...] Customers' quality requirements are emphasised in lean quality management theories. Pursuing the customers' quality requirements can reduce the uncertainty and the variability of a project [...] - Interviewee 11

Motivation management (such as providing motivation, changing attitudes, encouraging the workers to be self-conscious and creating a quality culture) is required in quality management. Quality-based lean construction management is quite helpful in improving soft management. The motivation management is mentioned to be improved by lean construction, as evidenced in the following:

[...] Workers are motivated, and their self-consciousness is increased by authority being transferred to the workers. Decentralised control is used to encourage workers to take responsibility for their assigned works [...] - Interviewee 11

#### **4.2.3.2 Limitations and requirements of quality-based lean construction approaches**

According to Interviewee 3 and 8, regardless of how advanced a lean quality management theory or technique is, it is based on one of the most basic principles of the complete symmetry of information. On-site information is needed for projects to be completed quickly and thoroughly. The current quality-based lean construction lacks an efficient way to collect on-site data. On-site information cannot be transferred to managers smoothly, which results in some decisions being made according to experience and not to the actual situation. Therefore, an efficient data collection tool is needed in quality-based lean construction.

Interviewee 6 reported that a massive amount of information is generated every day depending on how complicated a project is. Construction information is often stored in paper-based documents, which makes it difficult to find and hard to retain for a long time. Additionally, paper-based documents can take up much space and are hard to remove. In order to ensure the efficient and convenient use of construction information, it is necessary to find another way to store it.

According to Interviewee 9, the current visual management and Kanban techniques in lean quality management are based on graphs, cartoons and notice boards. The expression of digital information is seldom adopted on construction sites. The conventional ways of demonstrating information lack images. Moreover, customers' expectations are relatively easy to achieve through the demonstration of expressive information. Interviewee 3 further added, as evidenced in the following:

[...] The cooperation between participants in concurrent engineering is also beneficial for improving expressive information. Clearer expressions of information are required for quality-based lean construction management [...]  
- Interviewee 3

A limitation of quality-based lean construction with regard to improving standardisation is in the simplifying of standards. As Interviewee 5 stated, although lean visual management can help to explain standards in a visual way, it does not ensure standard simplification. Graphs, signals and notice boards are still not enough. A new visual tool is needed for quality-based lean construction management.

The limitation of the current quality-based lean construction management in terms of the LPS is that it lacks a simulation tool to simulate different plans. The alternative plans are difficult to test in a virtual world. This can influence the efficiency and accuracy of plans.

#### 4.2.4 Findings discussion of Project TZ

A comprehensive discussion that integrates the findings from the existing literature and the results from the case study is provided in response to answer the objective of the research. Therefore, the arrangement of this section is based on the following purposes:

- Summarising quality-based lean construction theories and quality-based lean construction techniques by utilising the new findings of the case study and cross-referencing them with the findings from the previous literature.
- Discussing the incentives, limitations and requirements of the current lean construction-based quality improvement approaches.

##### 4.2.4.1 A comprehensive summary of quality-based lean construction theories and quality-based lean construction techniques

The lessons learned from construction site can not only provide support to the existing literature but could also provide inspiration for future development in the field. All of the summarised results in this section have been obtained through a comprehensive analysis of the literature review findings and the results of the case study investigation.

According to the findings of the literature review in Chapter 2, there are five potential quality-based lean construction theories. Moreover, four potential quality-based lean construction theories have been found through the case study. Overlap exists between these theories. Detailed information is listed in Table 19.

Table 19: Quality-based Lean Construction Theories from the Literature Review and the Case Study

No.	Quality-based lean construction theories	Literature review	Case study
1	Proactive quality defect prevention culture	x	
2	Conversion to a quality-based mindset	x	x
3	Decentralised control- giving authority to worker	x	x
4	Customer quality requirements	x	
5	Pull-based quality management		x
6	Continuous quality improvement	x	



## **1) Quality-based lean construction theories**

### **(1). Proactive quality defect prevention culture**

The quality-based lean construction theory of the proactive quality defect prevention culture is found and confirmed by the literature review. According to Crosby (1979), high-quality construction can be achieved during first-time construction through built-in quality, which is the result of proactive quality defect prevention. Quality defects should be prevented during the process of construction, rather than inspected in the final product. According to the literature review, the most reasonable way to ensure construction quality is to prevent defects in advance. Creating a proactive quality defect prevention culture helps construction participants treat quality defects with positive preventive attitudes. Although the formation of proactive quality defect prevention culture was not proposed in the case study, some traces of proactive high-quality defect prevention could still be found. The implementation of the LPS, 5S management, Kanban and standardisation can be regarded as the concrete application of proactive quality defect prevention theory. Therefore, the proactive quality defect prevention culture can be considered a quality-based lean construction theory.

### **(2). Conversion to a quality-based mindset**

The influence of the conversion to a quality-based mindset on improving construction quality is confirmed in the literature review. No bottom line for quality defects should be allowed in construction. All construction participants are responsible for construction quality improvement. Participants need to shift their mindsets and ensure quality on their own.

The role of the conversion to a quality-based mindset has also been supported by the case study. According to the interview findings, only by mobilising every participant's enthusiasm for quality control and every participant being concerned about construction quality can the final delivery of construction products meet or exceed the customers' expectations. Quality can be improved through a mindset conversion, which has been learnt from years of experience applying lean construction at ZJ

Company. Therefore, the conversion to a quality-based mindset can be considered a quality-based lean construction theory.

### **(3). Decentralised control- giving authority to workers**

A number of studies are found in the existing literature on the correlation between decentralised control and construction quality improvement. With this theory, the authority of quality control is partly given to the workers. Site workers are encouraged to take the responsibility to improve construction quality (Misfeld and Bonke, 2004). On-site workers are required to inspect the quality of previous construction processes. Furthermore, they are also required to conduct self-inspections to ensure construction product quality after they finish their own work. This is the best way of reducing rework loss as the workers and equipment utilised in the previous stage have not to leave the current construction site for other construction tasks. The next stage of construction work can begin only after the quality of work is completely confirmed. Regarding the results of the case study, the interviewees also discussed transferring authority to the workers. The workers are well suited to identify quality defects by themselves. As interviewee 1 described, defects can be detected earlier by workers' observations and fixed at a lower cost when quality control authority is transferred to the workers. Additionally, workers are encouraged to take part in construction planning. The plan quality can also be improved due to workers' support. Therefore, decentralised control which gives authority to the workers can be considered a quality-based lean construction theory.

### **(4). Customer quality requirements**

According to the definition of quality discussed in Chapter 2, good quality is achieved by eliminating defects, delivering value to the customer and to meet the expectations of the customers. Quality requirements are one of the expectations of customers from a quality perspective. Recent studies emphasise that meeting customer quality requirements is a quality-based lean construction theory which aims to conduct all construction activities according to the customers' quality requirements. Due to the final goal of lean construction being to increase the customers' satisfaction, customer quality requirements are considered a quality-based lean construction theory.

#### **(5). Pull-based quality management**

Pull-based quality management is part of actual project application. Pull-based quality management emphasises using a pull approach to pull quality from back step construction work to front step construction work. The total quality is first pulled by the end-user customers, and then quality requirements are transmitted to the immediate customers. The overall quality requirement is pulled up and all on-site workers are responsible for meeting the quality requirements of both the immediate customers and the end-user customers. Pull-based quality management can achieve quality requirements quickly and accurately. The whole project quality can be improved with this method. Therefore, pull-based quality management can be considered a quality-based lean construction theory.

#### **(6). Continuous quality improvement**

Continuous improvement is one of the most important principles of lean construction. Quality is also one of the goals of continuous improvement. Although it is hard to achieve perfect quality, the quality goal of perfection should be pursued perpetually. According to findings from the literature review, continuous quality improvement improves construction quality in the following ways: continuous learning of lessons, continuous improvement of the construction process, continuous improvement of construction abilities and continuous improvement of quality awareness. Therefore, continuous quality improvement can be considered a quality-based lean construction theory.

#### **(7). Cooperation and communication**

Although cooperation and communication are not formally proposed in the documents of ZJ Company, its benefits in terms of quality improvement have been confirmed by experts working at the company. Quality improvement requires a cooperative work environment among the different participants. Optimising one's own benefits at the expense of others could prevent the continuous improvement of quality. Additionally, effective communication improves the cooperation between participants and avoids misunderstandings. This is the reason that establishing a cooperative and

communicative environment is important. Therefore, cooperation and communication can be considered a quality-based lean construction theory.

## 2) Quality-based lean construction techniques

According to the findings of the literature review in Chapter 2, there are four potential quality-based lean construction techniques. Moreover, five potential quality-based lean construction techniques have been found through the case study. Overlap exists between these techniques. Detailed information is listed in Table 20.

Table 20: Quality-based Lean Construction Techniques from Literature Review and Case Study

No.	Quality-based lean construction techniques	Literature	Case study
1	Last planner system	x	x
2	Visual management	x	
3	5S management		x
4	Kanban	x	x
5	Standardisation		x
6	First run study		x
7	Concurrent engineering	x	

### (1). Last planner system

As mentioned in the literature review, the LPS is one of the most important techniques of lean construction to improve construction quality. A bottom-up approach is adopted in the LPS. Last planners are encouraged to participate in the planning stage. The last planners' suggestions are usually given based on the actual construction site conditions, which makes construction plans relatively reasonable. The improvement of planning quality indirectly leads to the improvement of the quality of the whole construction project. Additionally, as the last planners are involved in making plans, they are familiar with the quality control priorities included in the plans. Last planners can help to avoid quality problems by paying attention to quality control priorities in advance when they participate in the actual construction. Strong evidence that LPM can improve construction quality was found regarding Project TZ. The LPS can really improve construction quality, as proven by a summary of years of implementation experience at ZJ Company. The results from reviewing the previous literature and

analysing the case study indicate that the LPS can be considered a quality-based lean construction technique.

## **(2). Visual management**

In reviewing the existing literature, it is found that visual management can help improve construction quality. Visual management offers an easy way of accessing standards and allowing for defects to be recognised immediately. Visual management places emphasis on using an intuitive way to transmit information. Figures, flow charts, communication boards and physical models are usually adopted to provide visual information, which improves the constructability of projects. The quality of a whole project can be indirectly improved by implementing visual management. Therefore, visual management can be regarded as a quality-based lean construction technique.

## **(3). 5S management**

The value of 5S management in quality improvement is proven through the case study. 5S management emphasises providing a comfortable working environment. Implementing 5S management can be helpful for arranging the layout of a construction site reasonably and for organising the working environment. Working efficiency and construction quality can be improved by making construction sites neat and orderly. Comparative research of before and after the use of 5S management was conducted in the project by employees of the company. The quality defects were reduced after 5S management was adopted. Therefore, 5S management can be considered a quality-based lean construction technique.

## **(4). Kanban**

The role of kanban in quality improvement is confirmed in both the literature review and the case study. Pull-based kanban is used to meet the demands of construction projects at the required quality level and the required quantities and to the required schedule. It is a useful approach to transferring information. The standardisation of on-site material processing and distribution is realised by implementing kanban. Different kinds of kanban were used in Project TZ to improve the construction quality by providing clear information and instructions. Therefore, kanban can be considered a

quality-based lean construction technique.

#### **(5). Standardisation**

Standardisation is used to provide the standards of projects for participants to obey. Repeated quality problems can be solved by creating a standardised operating manual. Standardisation is based on the continuous improvement principle, and the standard procedure can be updated when better approaches emerge. Standardisation helps workers to understand which construction products standard products and which operational construction procedures are standard procedures. Construction quality can be improved by implementing standardisation. Therefore, standardisation can be considered a quality-based lean construction technique.

#### **(6). First run study**

Although very little is found in the literature review discussing first-run studies from a quality perspective, positive answers were obtained through the interviews. A first-run study can benefit construction quality improvement in actual projects. First-run studies are used to help managers identify several alternative plans and choose the most suitable plan among the possible options. Construction quality can be improved by adopting a reasonable construction plan. Therefore, first-run studies can be considered a quality-based lean construction technique.

#### **(7). Concurrent engineering**

According to the results of the literature review, concurrent engineering is used to ensure design quality by connecting all the participants. Concurrent engineering results in a chain reaction for improving construction quality. Integrated design improves the constructability of design drawings. Any design that cannot be built or that is difficult to build can be revised and rectified. This method means that the construction team does not have to follow an unreasonable design in the process of construction, which improves the quality of the construction. Moreover, by participating in the design, the construction team can understand the design content better and can ensure that the design intention is considered in the construction. Therefore, concurrent engineering can be considered a quality-based lean construction technique.

#### **4.2.4.2 A summary of incentives, limitations and requirements of quality-based lean construction**

The detail discussion of incentives, limitations and requirements of quality-based lean construction from case study could be seen in section 4.2.3. According to the finding of case study, the incentives could be summarised as below:

- Lean construction facilitates the development of prevention culture
- Lean construction promotes workers' quality awareness
- Lean construction facilitates win-win cooperation
- Lean construction benefits continuous standardisation improvement
- Lean construction emphasises on customer requirements
- Lean construction improves motivation management

Moreover, the limitations and requirements are summarised:

- Information collection support and requirements
- Information storage requirements
- Vivid information expression requirements
- A visual and simulative tool is required

According to previous discussion, lean construction benefits construction quality through management theory and lacks tools to calculate, simulate, store and present data.

### 4.3 Case Study Findings for Project LX

#### 4.3.1 The background of the project

The LX project was located within the information industry and was based in Haidian District in Beijing. The project was divided into two phases. The floor area of the second phase was 69,700 m<sup>2</sup>. There were six levels over ground and two levels underground. A frame-core tube structure was adopted in this project, and a steel structure was partly used.

HY Company is a multinational group that integrates capital operation, real estate development, construction engineering and equipment manufacturing. HY Company began to apply BIM in the construction project in 2010. HY Company has rich experience in BIM implementation. This company is committed to actively cooperating with BIM software development companies. It is also one of the leading companies in China in BIM research. The project manager was invited by the government to create China's BIM application framework in 2015. There were 16 experts in the interviews. The information about interviewees in Company HY was listed in Table 21.

Table 21: List of the Interviewees for Company HY

Name	Designation	Construction experience (years)
1	Board of Director	More than 20
2	Board of Director	More than 25
3	Deputy Project Manager	More than 15
4	Vice-technical Director	More than 15
5	Technical Director	More than 10
6	BIM Manager	More than 5
7	Deputy Project Manager	More than 10
8	BIM Technologist	More than 5
9	BIM Technologist	More than 10
10	Board of Director	More than 15
11	Deputy Project Manager	More than 20
12	Construction Technologist	More than 5
13	Vice-technical Director	More than 15
14	BIM Manager	More than 10
15	Vice-technical Director	More than 10
16	Vice-technical Director	More than 15



### 4.3.2 Quality-based BIM applications

The quality-based BIM applications used in Project LX are identified in this section. The findings of quality-based BIM application are summarised in Table 22. Further detailed evidence in the form of qualitative data is provided and discussed below.

Table 22: Quality-based BIM Applications Identified in Project LX

No.	Quality-based BIM applications
1	BIM-based clash detection
2	BIM-based design joint inspection and technical disclosure
3	BIM-based construction plan simulation and optimisation
4	BIM-based design change management
5	BIM-based dynamic template display
6	BIM-based visual construction layout
7	BIM-based quality information management

#### 4.3.2.1 BIM-based clash detection

HY Company has rich experience in implementing BIM-based clash detection. BIM-based clash detection is used to check and adjust the space collision problems which exist in architectural, structural, water supply and drainage works. According to Interviewees 1, 3 and 12, a clash is usually presented as a space intersection or space collision between different elements. This situation is usually caused by miscommunication between different professional teams. Interviewee 1 further added:

[...] Clashes could be presented as the distance between element and element being less than a limitation. This limitation distance is set for a safety and quality consideration. When you use clash detection, remember to set a detection range [...] - Interviewee 1

According to Interviewees 2 and 8, BIM can produce a clash detection report which contains collision images, locations, components and conditions. The actual conditions can be double checked using the clash detection report. The collision points should be adjusted after checking. The application of BIM-based clash detection was explained by Interviewee 8:

[...] Firstly, the software, such as Revit, is used to build models of different disciplines and then integrate all discipline models together. Secondly, Revit's own clash detection function is used to detect the integrated model. Thirdly, professional management software such as Navisworks and Fuzor are adopted to conduct clash detection more detailly. Finally, the model is modified according to the clash detection report and improved construction plan [...] - Interviewee 8

The adoption of BIM-based clash detection dramatically improves the detection and correction of design defects, which enhances construction quality.

#### **4.3.2.2 BIM-based design joint inspection and technical disclosure**

Design drawing joint inspection and technical disclosure is a combined process to check design drawing together and conduct technical disclosure, which is popular in China (Chi, 2016). The joint inspection of drawings is an effective approach to pre-controlling construction quality. It aims to fully understand the design intent, optimise and modify design drawings and detect design defects. The joint inspection provides a certain degree of quality control in the early stages of construction.

BIM-based design joint inspection in China is uncommon (He, 2014). However, it was one of the most important BIM applications in Project LX. According to Interviewee 3, BIM was implemented in the joint design inspection. A 3D BIM model replaced traditional 2D-based design drawings to present the design intent. Visual information representation improves the efficiency and the quality of inspection work. Design defects can easily be detected in a 3D environment. Moreover, as Interviewee 5 mentioned, the related information could be extracted from the model at any time, which saved joint inspection time and improved the inspection quality.

Technical disclosure is used to help workers gain a detailed understanding of an entire project, including technical, quality, safety and construction requirements. Traditional technical disclosure relies on a large number of 2D drawings and text descriptions. The

technical disclosure of construction projects is generally hard for construction workers to understand.

According to Interviewees 4 and 5, each construction step and procedure can be displayed intuitively within BIM-based technical disclosure. Using BIM technology and a few necessary descriptions, technicians and workers can understand a whole project easily and accurately. The communication between designers and builders is convenient in a 3D virtual environment. Interviewee 1 also supported the importance of BIM in improving the quality of technical disclosure, evidenced in the following quote:

[...] Each project will have some complex building components or some special construction points that are difficult to describe with a 2D view. We set up the corresponding BIM model for these special situations and added the model to the technical disclosure materials. Meanwhile, we animated and simulated some important construction points during the technical disclosure meeting and discussed the possible construction methods of these points [...]  
- Interviewee 1

#### **4.3.2.3 BIM-based construction plan simulation and optimisation**

The quality of a construction plan can be improved by simulating and optimising it in BIM. According to Interviewees 5 and 6, 4D simulation was adopted in the planning phase in project LX. The construction procedures and content were presented through a 4D simulation technique. Additionally, as Interviewee 5 further mentioned, virtual construction was adopted for forming reasonable plans for the application of new technologies and materials. BIM could support the virtual construction of techniques, materials and equipment on a computer. The virtual construction could be repeated until a reasonable solution was obtained. Interviewee 6 described BIM functions in the construction plan simulation and optimisation:

[...] Since BIM has been adopted in construction planning, the quality of the plans is dramatically improved. Our managers are very confident in their plans because

the rationality of these plans has been validated by BIM [...] - Interviewee 6

#### **4.3.2.4 BIM-based design change management**

In the process of project construction, some unexpected problems in the design are sometimes encountered, and design drawings need to be changed. In the conventional design approach, design drawings need to be redrawn after design changes. Due to this complicated process of changing the drawings, it is difficult to update the on-site drawings in a timely manner. In the observation of Project LX, it was found that design changes often caused confusion between designers and builders.

BIM can reduce the negative impact of design changes. According to Interviewee 2, design changes can be achieved by modifying the parameters in a BIM model. The parameters in BIM all interact in relation to each other, and the whole model can be updated automatically to adapt to any modification. The floor plans, elevations and sections of the model are changed consistently to achieve a collaborative modification. Furthermore, the altered drawings can be automatically generated and exported via BIM, and the drawings can be instantly used to guide construction work. As Interviewee 5 mentioned, all of the participants could compare the model before and after the design changes by simply changing different parameters. This helped on-site workers to understand the intentions of the design and reduced errors relating to inconsistency in the model. Moreover, according to both Interviewees 2 and 5, screenshots of the BIM model were also attached to the design change reports in this project. The notifications of design changes were sent through the BIM platform. In general, BIM technology helped the participants to understand the changes intuitively and improved communication efficiency.

#### **4.3.2.5 BIM-based dynamic template display**

The entity construction templates used in a project usually take up much space, and the creation of templates takes much time. According to Interviewee 1, with the development of touch-sensitive displays, BIM-based dynamic templates gradually took the place of entity construction templates at HY Company. The construction control points, the dynamic construction model, the important construction joints and

the construction techniques could be magnified and presented through touch-sensitive displays on the construction site. Additionally, Interviewees 1 and three further explained that the on-site workers could obtain the information they needed from BIM. The BIM model contained more information than entity construction templates, which could support construction quality control and improve inspections.

#### **4.3.2.6 BIM-based visual construction layout**

Conventional construction site layouts are usually based on design drawings and managers' experience. This kind of construction site layout cannot adapt to changing construction site environment. In contrast, BIM helps managers to create a 3D visual construction site layout with construction site information. This was supported by Interviewees 3 and 5, as shown in the following statements:

[...] BIM-based visual construction layout is drawn up through BIM software before the commencement of the project. The construction area, material processing area, office area and living area are arranged reasonably in BIM. The BIM 3D model is also combined with the actual size parameters of the construction site to show the actual layout results of the construction site [...] - Interviewee 3

[...] Through years of application experience, BIM-based visual construction layout not only lays out the construction site but also benefits machinery layout. The influence of the area occupied and the height of the equipment is analysed through on-site machinery simulation [...] - Interviewee 5

As Interviewee 3 further explained, BIM-based construction layout can be updated according to actual construction site conditions.

#### **4.3.2.7 BIM-based quality information management**

Quality information management is one of the most important processes in the whole of the project. Quality information management is the basis of other quality improvement activities. In Project LX, BIM was used for quality information management. According to observations of the project, the inspection results, which

included quality inspection information, quality approval records, the images and videos of concealed works and scanned documents, were uploaded to the BIM model. The quality information was associated with the corresponding components in the model and became part of the attribute information of the component. The current quality inspection status of each component could be viewed in the model. The quality inspection information was classified and graded in the model, which facilitated the retrieval of the information.

According to Interviewees 14, various quality information is stored in BIM, as evidenced in the following statement:

[...] The material quality information is collected and uploaded into the BIM model. The material qualification certificate, warranty and inspection report are uploaded into the model and associated with each component. In addition, the information of quantity, qualified certificate, and quality warranty of construction equipment is stored in the model. Design change documents, operator and inspector information and construction environment are also important information in quality information management [...] - Interviewees 14

According to the experience of applying BIM-based quality information management in this project, it can be seen that construction quality is improved by retrieving information from the BIM database and learning lessons from past failures through the knowledge feedback mechanism of BIM. Quality management is improved by retrieving and learning lessons from well-managed quality information.

### **4.3.3 The incentives, limitations and requirements of quality-based BIM**

BIM is a revolutionary tool in the current construction industry. It updates computer-aided tools from 2D to 3D. Various information is contained in the model, which makes BIM a construction information database.

#### **4.3.3.1 Incentives in terms of quality requirements**

According to the requirements of Chinese construction quality improvement requirements, BIM not only improves conventional quality inspection, which aims to

ensure product quality, but it also enhances the construction process by ensuring proactive defect prevention. According to Interviewees 16:

[...] The visualisation and simulation mechanisms of BIM help on-site workers to understand design drawings easily. Construction plans can be made more reasonable through BIM, rather than relying on experience. This new tool helps managers to reduce the emergence of defects and to achieve a high-quality final product [...] - Interviewees 16

Cooperation is one of the most important characteristics of quality management. As Interviewee 7 stated, different participants in the construction process are all responsible for project quality.

[...] The participants need to work together to ensure the delivery of construction projects. BIM creates a connection between participants for transmitting information and communicating. The participants can communicate intuitively by using a 3D virtual model. In this way, the efficiency of cooperation is improved [...] - Interviewees 7

Interviewee 9 summarised that BIM works well with regard to information processing. It changes the information collection process. Some advanced information collection techniques are integrated into BIM to make the information collection process more efficient and accurate. Interviewee 9 further added that mobile devices could be adopted to upload current site information. This also avoids the repeated entry of information. The uploaded information is all stored in the model. Paper-based documents are replaced with a computer information database in the model. BIM can not only store quality information but also retrieve information conveniently. It helps to avoid similar defects from repeatedly happening in future projects.

#### **4.3.3.2 Limitations and requirements based on BIM-based quality improvement attempts**

According to Interview 13, BIM does have many advantages for information

processing as a computer-aided tool, but it does not have a close connection with management in the Chinese construction industry, as evidenced in the following statement:

[...] BIM should not be confined to be used as only a tool, but also influences construction quality management. The separate application of BIM cannot solve all quality problems in construction projects. It is easier for BIM to be guided by a management philosophy to improve construction quality [...] - Interviewees 13

#### **4.3.4 Findings discussion of project LX**

The findings from literature and case study were discussed together in this section. According to the research objectives, there were two main parts needed to be discussed, which were:

- a) To summarise quality-based BIM mechanisms and quality-based BIM applications through analysing findings from literature review and case study.
- b) To summarise the findings of incentives, limitations and requirements of quality-based BIM approaches

##### **4.3.4.1 A comprehensive summary of quality-based BIM mechanisms and quality-based BIM applications**

The quality-based BIM approaches were summarised from learning literature review and case study results.

##### **1) Quality-based BIM mechanisms**

Six potential quality-based BIM mechanisms are summarised from literature review. They are 'visualisation', 'simulation and calculation', 'dynamic', 'collaboration', 'integration' and 'coherence'. These potential quality-based BIM mechanisms are discussed below (see Table 23). These mechanisms which were identified from literature review were asked in interview, and all of them were accepted by interviewees. However, the detail contents of quality-based BIM mechanisms were mainly achieved from literature review.



Table 23: Potential Quality-based BIM Mechanisms from Literature Review and Case study

No.	Potential quality-based BIM mechanisms	Literature Review	Case study
1	Visualisation	X	X
2	Simulation and calculation	X	X
3	Dynamic	X	X
4	Collaboration	X	X
5	Integration	X	X
6	Coherence	X	X

### **(1). Visualisation**

The detail discussion of visualisation mechanism from literature review could be seen in Chapter 2. This mechanism was accepted by all interviewees. Visualisation mechanism helps quality improvements in the following aspects:

- Improve the spatial cognition of construction executives
- Facilitate illustration and interpretation of space relationships
- Visually present complex construction components
- Provide detailed node drawing with node profile

According to the quality-based BIM applications, the mechanism of visualisation has various practical applications. Almost all the practical applications of BIM in quality improvement benefit from the visualisation mechanism. Hence, visualisation is vital in quality-based BIM mechanism.

### **(2). Simulation and calculation**

The detail discussion of simulation and calculation mechanism from literature review could be seen in Chapter 2. This mechanism was accepted by all interviewees. Simulation and calculation mechanism helps quality improvements in the following aspects:

- Identify best practices

- Identify benefits and drawbacks of current construction plan
- Detect design defect through roaming
- Calculate the rationality of construction components within a space

According to quality-based applications, the simulation and calculation mechanism is widely used in BIM applications, such as BIM-based clash detection, BIM-based construction plan simulation and optimization, BIM-based visual construction layout and so on. Therefore, simulation and calculation mechanism can help BIM play an important role in improving quality.

### **(3). Dynamic**

The detail discussion of dynamic mechanism from literature review could be seen in Chapter 2. This mechanism was accepted by all interviewees. Dynamic mechanism helps quality improvements in the following aspects:

- Timely input quality related information
- Timely modify quality related information
- Timely delete quality related information
- Timely store quality related information

The timely quality information support is the basis of construction quality management. BIM-based quality information management is achieved through a dynamic BIM mechanism. Hence, Dynamic should be considered as one of quality-based BIM mechanisms.

### **(4). Collaboration**

The detail discussion of collaboration mechanism from literature review could be seen in Chapter 2. This mechanism was accepted by all interviewees. Collaboration mechanism helps quality improvements in the following aspects:

- Enhances collaborative working environments
- Improve construction information transmission

- Enhance visual exhibition, enriching construction databases and strengthening parametric 3D interaction
- Remote communication
- reduce the duplicated input of information
- Avoids redundancy, ambiguity and errors within the data

Moreover, some quality-based BIM applications such as BIM-based design joint inspection and technical explanation could be achieved with the help of collaboration mechanism. Therefore, collaboration mechanism is regarded to benefit construction improvement.

### **(5). Integration**

The detail discussion of collaboration mechanism from literature review could be seen in Chapter 2. This mechanism was accepted by all interviewees. Integration mechanism helps quality improvements in the following aspects:

- Provide a platform for the integration of other advanced techniques
- Improve the accuracy of construction work
- Reduce the quality inspection omission
- Integrate with information database.

The integration mechanism mainly benefits for BIM-based quality inspection in quality-based applications. It could be one of quality-based BIM mechanisms.

### **(6). Coherence**

The detail discussion of coherence mechanism from literature review could be seen in Chapter 2. This mechanism was accepted by all interviewees. Coherence mechanism helps quality improvements in the following aspects:

- Automatically update model to adapt to the modification
- Maintain information coherence
- Reduce inconsistent information errors

Coherence mechanism makes BIM adapt to the requirements of various quality-based applications, such as BIM-based design change. Therefore, coherence mechanism is considered to be a quality-based BIM mechanism.

## 2) Quality-based BIM applications

The quality-based BIM applications were summarised from literature and case study together (see Table 24). These eight potential BIM applications were discussed below.

Table 24 Quality-based BIM Applications from the Literature Review and the Case Study

No.	Quality-based BIM applications	Literature Review	Case study
1	BIM-based clash detection	x	x
2	BIM-based design joint inspection and technical disclosure		x
3	BIM-based construction plan simulation and optimisation	x	x
4	BIM-based design change management		x
5	BIM-based dynamic template display		x
6	BIM-based visual construction layout		x
7	BIM-based quality information management		x
8	BIM-based quality inspection	x	

### (1). BIM-based clash detection

The detail discussion of BIM-based clash detection from literature review could be seen in Chapter 2 and findings from case studies could be seen in Chapter 4. From literature review, BIM-based clash detection helps quality improvements in the following aspects:

- Automatically detect the clashes such as incompatible parameters, overlapping spatial elements and too close elements
- Integrate models from different disciplines together to detect clashes
- Provide sectional views for any of the elements in the model
- Provide an intuitive approach to review design, such as utilising roaming

The findings come from case study are similar to literature review results. Some of content is repetitive. The new findings identified in case study are illustrated below.

- Produce a clash detection report which contains collision images, locations, components and conditions.

Therefore, BIM-based clash detection is considered to be a quality-based application.

## **(2). BIM-based design joint inspection and technical disclosure**

The detail discussion of BIM-based design joint inspection and technical disclosure from case study could be seen in Chapter 4. From case study, BIM-based design joint inspection and technical disclosure help quality improvement in the following aspects:

- Fully understand the design intent, optimise and modify design drawings and detect design defects.
- Improve the efficiency and the quality of design drawing inspection work through visual information representation
- Help builders gain a detailed understanding of an entire project, including technical, quality, safety and construction requirements.
- Create a 3D virtual environment to facilitate communication between designers

Therefore, BIM-based design joint inspection and technical disclosure is considered as a quality-based BIM application

## **(3). BIM-based construction plan simulation and optimisation**

The detail discussion of BIM-based construction plan simulation and optimisation from literature review could be seen in Chapter 2 and findings from case studies could be seen in Chapter 4. From literature review, BIM-based clash detection helps quality improvements in the following aspects:

- Planners can have a reasonable understanding of the whole plan by reviewing the

#### 4D simulation results

- Present the quality control points in the construction procedure
- Discover the conflicts between the construction teams in time and space in the cross work
- Repeatedly verify and adjust plan through construction simulation.

The findings come from case study are similar to literature review results. Most of content is repetitive. Therefore, BIM-based construction plan simulation and optimisation are considered to be a quality-based BIM application.

#### **(4). BIM-based design change management**

The detail discussion of BIM-based design change management from case study could be seen in Chapter 4. From case study, BIM-based design change management helps quality improvement in the following aspects:

- Design changes can be easily achieved by modifying the parameters in a BIM model
- The parameters in BIM all interact in relation to each other, and the whole model can be updated automatically to adapt to any modification
- The altered drawings can be automatically generated and exported via BIM
- BIM technology helps the participants to understand the changes intuitively and improved communication efficiency.

Therefore, BIM-based design change management is considered as a quality-based BIM application

#### **(5). BIM-based dynamic template display**

The detail discussion of BIM-based dynamic template display from case study could be seen in Chapter 4. From the case study, BIM-based dynamic template display helps quality improvement in the following aspects:

- The construction control points, the dynamic construction model, the important

construction joints and the construction techniques could be magnified and presented through touch-sensitive displays on the construction site

- On-site workers could obtain the information they needed from BIM template

Therefore, BIM-based dynamic template display is considered as a quality-based BIM application

#### **(6). BIM-based visual construction layout**

The detail discussion of BIM-based visual construction layout from case study could be seen in Chapter 4. From case study, BIM-based visual construction layout helps quality improvement in the following aspects:

- The construction area, material processing area, office area and living area are arranged reasonably in BIM.
- The BIM 3D model is also combined with the actual size parameters of the construction site to show the actual layout results of the construction site
- The influence of the area occupied, and the height of the equipment is analysed through on-site machinery simulation

Therefore, BIM-based visual construction layout is considered as a quality-based BIM application

#### **(7). BIM-based quality information management**

The detail discussion of BIM-based quality information management from case study could be seen in Chapter 4. From case study, BIM-based quality information management helps quality improvement in the following aspects:

- All necessary quality information is stored in BIM
- The quality information was associated with the corresponding components in the model and became part of the attribute information of the component.
- The current quality inspection status of each component could be viewed in the model.

- The quality inspection information was classified and graded in the model, which facilitated the retrieval of the information.
- Construction quality is improved by retrieving information from the BIM database and learning lessons from past failures through the knowledge feedback mechanism of BIM.

Therefore, BIM-based quality information management is considered as a quality-based BIM application

#### **(8). BIM-based quality inspection**

The detail discussion of BIM-based quality inspection from literature review could be seen in Chapter 2. From literature review, BIM-based quality inspection helps quality improvements in the following aspects:

- BIM optimises quality inspection plans
- BIM changes the way that quality information is collected on-site
- BIM changes the way that quality information is collected on-site
- BIM changes the way of comparing quality information
- BIM optimises quality modification

Therefore, BIM-based quality inspection is considered to be one of quality-based BIM applications.

#### **4.3.4.2 A summary of incentives, limitations and requirements of quality-based BIM approach**

The detail discussion of incentives, limitations and requirements of quality-based BIM approach from case study could be seen in Section 4.3.3. According to the finding of case study, the incentives could be summarised as below:

- Visualisation and simulation mechanisms make BIM could meet the requirements of proactive prevention
- BIM is a powerful data processing tool



- BIM is a cooperation platform
- BIM is an information repository

Moreover, the limitations and requirements are summarised:

- BIM requires a theory guide

According to previous discussion, BIM meets the requirements of quality improvement from the tool level. However, its implementation needs the help of proper management theory.

#### **4.4 The Discussion of Feasibility of Integrating Lean Construction and BIM to Improve Chinese Construction Quality through Case Study Results**

The wide acceptance of lean construction and BIM in the construction industry proves their value in terms of construction costs, schedules and quality (Bhatla and Leite, 2012). The implementation of lean construction and BIM is helpful for achieving quality success. However, there is a lack of academic research on the quality-based integrated application of lean construction and BIM. In this study, the feasibility of integrating lean construction and BIM to improve construction quality is analysed from the perspective of construction quality requirements.

Lean construction is a kind of philosophy which strengthens management. It can fulfil the requirements of construction quality improvement, such as ‘prevention mentality’, ‘long-term consideration of quality-oriented mindset change’, collaborative plans and motivation management through its lean theories like ‘cooperation and communication’ and ‘continuous quality improvement’. A detailed discussion of this can be found in Chapter 2. However, the results of applying lean construction for improving construction quality are not all positive. Some lean philosophies have gradually become slogans in the Chinese construction industry. However, lean construction is weak with regard to processing construction information. Its applications are still based on the conventional information processing approach, which results in on-site information not being transferred to managers completely and quickly (Soibelman and

Kim, 2002). Furthermore, the quality requirements of collaborative plans are not fully achieved through lean construction. The main characteristic of collaborative planning is gaining a deeper understanding of planned activities in advance, which requires robust information support (Dave et al., 2013). However, the practical role of lean construction in planning is weak because it lacks information support. Moreover, lean construction requires an efficient tool to store massive information and present it in a clear way. An information reserve is needed for fulfilling the quality requirement of continuous improvements to standardisation. Paper-based information storage techniques are often adopted in lean construction-based projects, which results in difficulties relating to information retrieval and retention. Paper-based documents can also take up much space and are hard to remove. Furthermore, there are cooperation benefits from sharing information in a clear way. The current information expression techniques are not sufficient enough, and clearer expressions of information are required by lean construction to improve construction quality. In general, lean construction can partly fulfil the current construction quality requirements, but it requires an efficient information tool to support its application from a quality perspective.

BIM is a set of tools which contains various construction information. BIM can improve construction quality by providing information support. The current quality requirements of proactive prevention of defect, effective cooperation, continuous improvements through standardisation and collaborative plans can benefit from the implementation of BIM. Similar to the situation of lean construction, the application of BIM alone cannot solve quality problems thoroughly. Although BIM is a recognised tool for improving construction quality, it still has limitations in its implementation. BIM requires management concepts to guide and facilitate its application. The application effect of BIM on quality improvement is strongly influenced by the management environment. The role of BIM in quality improvement can be strengthened in a management environment which places emphasis on predictability, discipline, collaboration and experimentation (Dave et al., 2013).

BIM is a form of transformative information technology which provides a tool to

realise quality improvement functions. Lean construction is a mindset that guides all of the appropriate tools, rather than being a set of tools itself. It has advantages in providing a conceptual approach to construction quality improvement, but it is weak in its application (Wang, 2012). Lean construction and BIM are complementary in many aspects. With regard to the quality perspective, lean construction is expected to provide a management philosophy that guides the application and development of BIM, and BIM can provide an implementation foundation for the results that lean construction is expected to achieve.

There are four kinds of integration relationship between quality-based lean construction approaches and quality-based BIM approaches. These integration relationships are:

- Quality-based BIM approach contributes directly to quality-based lean construction goals
- Quality-based BIM approach contributes indirectly to quality-based lean construction goals
- An integrated information platform which is enabled by quality-based BIM approach contributes directly or indirectly to quality-based lean construction goals
- Quality-based lean construction guides quality-based BIM application

#### **Quality-based BIM contributes directly to quality-based lean construction goals**

Some quality-based BIM mechanisms directly align with quality-based lean construction theories. The BIM mechanisms of ‘visualisation’ and ‘simulation and calculation’, for instance, provide an intuitive way of detecting clashes. The clashes can be highlighted in a clash detection report. Quality defects are prevented in the virtual construction process before construction begins, so time and cost waste caused by rework can be avoided in advance.

The quality-based lean construction theory of creating a proactive quality defect prevention culture places emphasis on a thinking transformation, which encourages the adoption of prevention instead of inspection as much as possible. The quality-based BIM mechanisms of ‘visualisation’ and ‘simulation and calculation’ can prevent

defects from happening in a virtual environment before the actual occurrence of quality defects. This could be a possible direct contribution of quality-based BIM approach to quality-based lean construction theory.

**Quality-based BIM contributes indirectly to quality-based lean construction goals**

Sometimes, quality-based BIM mechanisms do not directly contribute to quality-based lean construction goals, but they do provide ancillary services to obtain quality-based lean construction goals easily, which indirectly influences quality-based lean construction goals. This is exemplified in the relationship between the lean construction theory of conversion to a quality-based mindset and its collaboration with the BIM mechanism. The collaboration mechanism means that BIM can provide a collaboration platform for all participants. Different participants can communicate information through BIM. The work tasks and responsibilities of each participant can be viewed through the BIM platform clearly. Participants know their tasks and responsibilities before their work begins. Furthermore, the participants can understand their colleagues' current work quality conditions through the efficient collaboration mechanism of BIM. The participants' quality awareness can be cultivated and supervised through the deep understanding of the work and responsibilities, as well as the efficient communication between colleagues and the pressure from colleagues to provide high-quality work. The collaboration mechanism of BIM does not directly influence the quality mindset, but it could be a potential indirect contribution of quality-based BIM approach to quality-based lean construction goals.

**An integrated information platform which is enabled by quality-based BIM contributes directly or indirectly to quality-based lean construction goals**

Due to the integrated mechanism of BIM, BIM as a platform can incorporate other techniques to contribute directly or indirectly to lean goals. The example of BIM-based quality inspection provides evidence for this relationship. 3D laser scanning techniques and AR techniques are usually combined and implemented with BIM. These integrated implementations change the way that construction site information is collected. The quality and efficiency of information collection are dramatically improved. Inspection quality is ensured by adopting an integrated information

platform. Decentralised quality control is an important quality-based lean construction theory. It aims to motivate the working enthusiasm of the workers in terms of quality improvement and to find quality defects at a low cost. At present, there is a lack of tools available for workers to detect quality problems efficiently. BIM-based 3D scanning information platforms and BIM-based AR information platforms could provide these tools. As far as the integrated mechanism is concerned, the integrated BIM information platform can contribute to quality-based lean construction goals.

#### **Quality-based lean construction guides quality-based BIM application**

Quality-based lean construction theories provide an implementation environment and conceptual guidelines for effective quality-based BIM implementation. The difficulties of BIM implementation are reduced by integrating BIM with quality-based lean construction theory. An example of this relationship is related to pull-based quality management and the BIM integrated mechanism. BIM, as mentioned above, can be a platform for integrating different techniques, such as 3D laser scanning and AR, to enhance construction quality inspection. Although BIM is an efficient tool to improve quality, managers also need a management philosophy to guide the use of BIM. Pull-based quality management, as part of a lean construction theory, provides a conceptual approach to guiding BIM implementation. In pull theory, the workers in the current construction process are responsible for meeting the quality requirements of the next construction process. The workers in the next construction process are responsible for inspecting the work quality of the previous process and choosing whether to accept it. BIM-based inspection can be adopted at this point. According to pull-based quality management, BIM is adopted by the workers in the next process to enhance quality inspection. quality-based BIM application is guided by quality-based lean construction theory.

#### **4.5 Summary**

This chapter has presented the discussion of finding from case studies. According to the case study results in Project TZ, four quality-based lean construction theories and five potential quality-based lean construction techniques were identified. These findings from the case study were combined and discussed with the results of the

literature review. The discussion result was that seven quality-based lean construction theories and seven quality-based lean construction techniques could help improve construction quality. According to the case study results in Project LX, seven quality-based BIM applications were identified. These findings were combined and discussed with the results of the literature review. The discussion result was that six quality-based BIM mechanisms and eight quality-based BIM applications could help improve construction quality. The above research in case studies provides a solid foundation for further investigating the interactions of quality-based lean construction approaches and quality-based BIM approaches.

The incentives, limitations and requirements were discussed in this section. This discussion facilitates the feasibility research. The feasibility of integrating lean construction and BIM to improve construction quality was confirmed through analysing the incentives, limitations and requirements, and the requirements of Chinese construction quality improvement together. Moreover, four general relationships between quality-based lean construction and quality-based BIM were identified.

## **Chapter 5: Survey Results**

### **5.1 Introduction**

This chapter presents the results of interviews which were designed to investigate the interactions between identified quality-based lean construction approaches and quality-based BIM approaches. 22 experts were selected as interviewees in this research (see Section 3.6.3). The interviews were based in China. The interviewees were asked to comment on the interactions between identified quality-based lean construction approaches and quality-based BIM approaches. The interview results were recorded, analysed and summarised.

### **5.2 The Importance of Integrating Lean Construction and BIM to Improve Construction Quality**

The interviewees were asked about the importance of integrating lean construction and BIM to improve construction quality. Nearly all of them (20 of 22) indicated that the integrated application of lean construction and BIM is important for improving construction quality. Additionally, at least two-thirds of those interviewees had experienced improvements in quality by integrating lean construction and BIM. As Interviewee 2 mentioned,

[...] Unique lean management theories combined with efficient BIM techniques can greatly improve schedule cost and quality [...] -Interviewee 2

### **5.3 The Exploration of the Quality-based Interactions between Lean Construction and BIM**

#### **5.3.1 The strategical interactions between quality-based lean construction theories and quality-based BIM mechanisms**

The quality-based theoretical interactions between lean construction and BIM that were identified through the interviews are discussed in this section. According to the interview results, 17 important interactions were identified (see Table 25).

Table 25: The quality-based Strategic Interactions from Survey

No.	The quality-based strategic interactions
1	Proactive quality defect prevention culture -Visualisation
2	Proactive quality defect prevention culture - Simulation and calculation
3	Conversion to a quality-based mindset - Visualisation
4	Conversion to a quality-based mindset - Simulation and calculation
5	Conversion to a quality-based mindset - Collaboration
6	Decentralised control- giving authority to worker-Visualisation
7	Decentralised control-giving authority to worker -Simulation and calculation
8	Decentralised control-giving authority to worker- Dynamic
9	Decentralised control- giving authority to worker- Integration
10	Customer quality requirements – Dynamic
11	Customer quality requirement – Collaboration
12	Customer quality requirements – Coherence
13	Pull-based quality management – Visualisation
14	Pull-based quality management – Collaboration
15	Pull-based quality management – Integration
16	Continuous quality improvement – Dynamic
17	Cooperation and communication – Collaboration

#### 5.3.1.1 Proactive quality defect prevention culture -Visualization

18 of 22 (82%) interviewees agreed that visualisation is helpful in achieving the proactive quality defect prevention culture. The interviewees who agreed with this statement shared the view that the improvement of the quality defect prevention capability can affect the formation of a quality prevention culture. An example was given by Interviewee 2:

[...] BIM is a visualised model which uses people's visual perceptions to prevent quality problems before they occur. This avoids only solving problems after they occur [...]-Interviewee 2

#### 5.3.1.2 Proactive quality defect prevention culture- Simulation and calculation

All of the interviewees agreed that there is a positive connection between the proactive quality defect prevention culture and simulation and calculation. More than half of the interviewees recognised the importance of a reasonable plan for quality prevention, for example, as Interviewee 4 stated:

[...] The best construction plan is achieved through simulation and calculation,



which lets the construction site be controlled and prevents quality defects from occurring [...] -Interviewee 4

Furthermore, BIM can support simulated roaming and calculations in a virtual environment; the design intention can be experienced through roaming before the actual construction begins.

#### **5.3.1.3 Quality-based mindset conversion-Visualisation**

13 of 22 (60%) interviewees reported that the conversion to a quality-based mindset and visualisation have a strong positive relationship. On-site workers can understand final construction products more intuitively through a visual model. According to Interviewee 15:

[...] The workers are very clear about what kind of work is consistent with the model, which indirectly helps to improve workers' quality awareness [...] - Interviewee 15

#### **5.3.1.4 Conversion to quality-based mindset - Simulation and calculation**

15 of 22 (68%) interviewees held the view that the conversion to a quality-based mindset can benefit from simulation and calculation. They shared the same view that,

[...] Through virtual construction, workers can intuitively know how to do their work and when to do it. A thorough understanding of construction technology helps workers to improve their quality consciousness, which helps convert to a quality-based mindset [...] -Interviewee 12

However, three of the interviewees argued that the potential to integrate simulation and calculation and quality-based mindset conversion is limited. The reasons were further explained by Interviewee 6:

[...] Quality-based mindset conversion is a personal intention, and it has

nothing to do with tools [...] -Interviewee 6

The rest of the interviewees were neutral on this issue.

#### **5.3.1.5 Quality-based mindset conversion- Collaboration**

15 of 22 (68%) interviewees agreed that there is an interaction between the conversion to a quality-based mindset and collaboration. This was illustrated by Interviewee 20:

[...] BIM could be used as a platform for cooperation, which facilitates communication. Meanwhile, each participant knows others' construction responsibilities through communication in BIM. This allows participants to know the impact of their work on others' work, which indirectly promotes workers' attention to building quality [...] -Interviewee 20

Around three-fifths of the interviewees also affirmed the indirect relationship between the conversion to a quality-based mindset and collaboration.

#### **5.3.1.6 Decentralised control- giving authority to the worker- Visualisation**

An overwhelming majority of the interviewees (21 of 22) affirmed the positive effects of integrating decentralised control - giving authority to the workers and visualisation. However, more than half of the interviewees emphasised the simpler and more straightforward characteristics of visualised BIM, for example,

[...] When the authority of quality control is delegated to workers, managers will encounter a problem of workers' low professionalism. In view of this situation, the tools should be simpler and more straightforward, such as a visualised 3D model [...] -Interviewee 11

#### **5.3.1.7 Decentralised control- giving authority to the workers - Simulation and calculation**

All interviewees made it clear that there is a positive relationship between decentralised control which gives authority to the workers and simulation and

calculation. When decentralised management is used, the workers participate in the process of making plans, and they are empowered to present their own views on future plans. The value of these suggestions can be validated through simulation and calculation in BIM. This was reinforced by Interviewee 17, who stated that:

[...] The rationality of a plan is ensured through simulation and calculation in BIM, which supports the implementation of the LPS [...] -Interviewee 17

#### **5.3.1.8 Decentralised control- giving authority to worker- Dynamic**

The vast majority of the interviewees (20 of 22) agreed that dynamic plays a positive role in decentralised control- gives authority to the workers. Interviewees 12, 21 and 22 also believed that the authority given to workers should not be unlimited:

[...] The authority needs to be supervised and controlled. The quality information from construction sites is constantly fed back to managers through BIM, which facilitates their analysis and handling [...] -Interviewee 21

Quality can be controlled by quality information dynamically supporting.

#### **5.3.1.9 Decentralised control- giving authority to worker- Integration**

All of the interviewees emphasised the importance of integration in decentralised control - gives authority to the workers when they were asked to give their suggestions on investigating interactions between quality-based lean construction and quality-based BIM. All agreed that BIM is a comprehensive platform that can integrate many advanced technologies in the quality inspection process, such as AR and 3D laser scanner techniques. Workers are given quality control authority to inspect the work quality of the previous processes. This was supported by Interviewee 5, who stated that :

[...] BIM improves the quality inspection ability through the integration

mechanism, which directly improves the quality of workers' inspection work  
[...] -Interviewee 5

#### **5.3.1.10 Customer quality requirements-Dynamic**

An overwhelming majority of the interviewees (21 of 22) believed that dynamic plays a positive role in customer quality requirements. With regard to the requirements of lean construction, the customers' quality requirements should be constantly considered. Interviewee 11 reported that:

[...] The quality of the construction site should be reported to the customer in real time. Therefore, a stable source of information, such as BIM, that can provide the latest information in time is needed [...] -Interviewee 11

#### **5.3.1.11 Customer quality requirements- Collaboration**

All of the interviewees supported a relationship between collaboration and customer quality requirements. They shared the same view that as Interviewee 14:

[...] BIM provides a collaboration platform for collaborating with customers. The information can be transmitted on this platform without hindrance. The application of a BIM collaboration platform facilitates the communication of quality requirements between the constructor and the customers [...] -Interviewee 14

#### **5.3.1.12 Customer quality requirements - Coherence**

The interaction between customer quality requirements and coherence is mainly reflected in how BIM meets the customers' changing quality requirements. 19 of 22 (86%) interviewees agreed that this interaction is positive. According to Interviewee 16,

[...] Since the quality needs of customers are changeable, construction design needs to be changed quickly and accurately at any time. BIM is a coherence model, and any changes are automatically and quickly updated into the whole

model, so it is well suited for this constant rapid change [...]-Interviewee 16

#### **5.3.1.13 Pull-based quality management - Visualisation**

Within pull-based quality management, the quality requirements of the next construction stage are the quality acceptance standards of the current construction stage. Interviewee 3 reported that:

[...] The visualisation of BIM provides support for the intuitive representation of quality requirements, which is convenient for workers to understand [...]-Interviewee 3

This interaction was identified by 19 of 22 (86%) interviewees.

#### **5.3.1.14 Pull-based quality management - Collaboration**

The core concept of pull-based quality management is transmitting quality requirements from back stage to front stage in consecutive construction stages. According to Interviewee 19,

[...] Because the pull system requires continuous quality requirement information transmission, a communication and cooperation platform such as BIM is needed to transmit information [...]-Interviewee 19

About 18 of 22 (82%) of the interviewees agreed that collaboration is helpful in achieving pull-based quality management.

#### **5.3.1.15 Pull-based quality management- Integration**

All interviewees confirmed the positive relationship between pull-based quality management and integration. As Interviewee 10 mentioned,

[...] Inspection work exists in pull-based quality management due to the next level of workers needing a quality check on the current job. BIM can effectively improve the quality and efficiency of inspections [...]-Interviewee

The positive role of integrated BIM in pull-based quality management is obvious.

#### **5.3.1.16 Continuous quality improvement- Dynamic**

17 of 22 (77%) interviewees suggested this interaction. Lean construction requires an unremitting pursuit of quality. BIM is a tool for constantly collecting, processing and storing information. Managers can learn from the lessons and experiences of past projects through the information stored in BIM and can then achieve the goal of continuous quality improvement. This was supported by Interviewee 11, who stated:

[...] Consider the past, and you shall know the future. BIM as an information repository continuously stores timely construction information, which provides an approach to retrieving past data [...] -Interviewee 11

#### **5.3.1.17 Cooperation and communication- Collaboration**

Although cooperation and communication are a lean construction theory, and collaboration is a BIM mechanism, they share the same meaning. Cooperation and communication and collaboration both place emphasis on developing a win-win result. All of the interviewees agreed with this interaction. Interviewee 11 reported that,

[...] Cooperation and communication are the core parts of lean construction. Only through continuous cooperation can quality success be achieved. The collaboration mechanism of BIM makes BIM an effective tool for lean cooperation and communication [...]. Interviewee 11

### **5.3.2 The implementation interactions between quality-based lean construction techniques and quality-based BIM applications**

The implementation interactions between quality-based lean construction techniques and quality-based BIM applications which were identified through the interviews are discussed in this section. According to the interview results, 11 important interactions were identified (see Table 26).

Table 26: The quality-based implementation interactions from survey

No.	The quality-based implementation interactions
1	Last planner system-BIM-based design joint inspection and technical disclosure
2	Last planner system-BIM-based construction plan simulation and optimisation
3	Last planner system-BIM-based quality information management
4	Visual management-BIM-based dynamic template display
5	5S management-BIM-based visual construction layout
6	Kanban-BIM-based information management
7	Kanban-BIM-based quality inspection
8	Standardisation-BIM-based dynamic template display
9	Standardisation-BIM-based quality information management
10	First run study-BIM-based construction plan simulation and optimisation
11	Concurrent engineering-BIM-based clash detection

#### **5.3.2.1 Last planner system - BIM-based design joint inspection and technical disclosure**

All interviewees shared the view that the LPS and BIM-based design joint inspection and technical disclosure will have a positive interaction. Approximately two-thirds of interviewees also believed that BIM provides a visualised environment to help planners to understand designs and to improve communication between the designers and the planners. Around three-quarters of the interviewees also highlighted that the visualisation of BIM also improves the quality of design drawing check-up, which ensures the design drawing quality. The planner in the last planner system could conduct the plan according to the quality design drawing and deeply understand the design intention in the master plan. The plan quality benefits from BIM

#### **5.3.2.2 Last planner system - BIM-based construction plan simulation and optimisation**

All interviewees agreed that BIM-based construction plan simulation and optimisation could dramatically improve the LPS implementation results. Interviewee 6 claimed,

[...] 4D BIM could dynamically display the construction plan according to the set time schedule. The construction procedures and contents are presented with 4D BIM. The planner could view the plan result intuitively, which helps

planning process. Every single aspect of plan quality in the last planner system is improved. The process of rehearsal and iterative optimisation of plans increases the liability of construction plan and improves the quality of plan [...]-Interviewee 6

The interviewees who supported this interaction explained this view in detail. The BIM-based construction plan simulation and optimisation played an important role in master and phase schedule in LPS. What tasks SHOULD be done were presented through BIM 4D model. The simulation of 4D BIM could help planner and other participants to get insights into the whole construction process. It helped planners to schedule the plan well.

Look-ahead plan is a prepare planning which is about 6 weeks before construction work begin. It will be used to focus on what could be happened in the future and take actions to fulfil future requirements (Munje and Patil, 2014). According to Interviewee 11, the next weeks of work which were displayed in the look-ahead plan benefited from BIM-based simulation and optimisation:

[...] In the look-ahead plan, the BIM-based simulation and optimisation help planners to select what CAN do among SHOULD do tasks for the next 6 weeks. The constrains of completing tasks are detected and solved through simulation and optimisation in BIM model [...]-Interviewee 11

The last planners are involved to create weekly work plan which plans the WILL done works in the next week (Munje and Patil, 2014). Weekly work plan requires commitments by last planners (especially foremen) to complete their activities in a certain manner and a certain sequence as planned (Engineers Australia, 2012). According to interviewees, the suggestions from last planners were tested and validated through BIM-based simulation and optimisation. The reliable ideas were accepted. Through the application of LPS and BIM-based simulation and optimisation, it greatly promoted the enthusiasm of workers and ensured the quality of the plan. Additionally, it is even possible to use mobile facilitates like smartphones and tablets



to simulate the detail construction processes which helped last planners to explain the weekly plan to the field workers.

#### **5.3.2.3 Last planner system - BIM-based quality information management**

An overwhelming majority of the interviewees (21 of 22) believed that it is important to integrate the LPS and BIM-based quality information management. Four-fifths of the interviewees stated that the implementation of the LPS relies on the support of much construction information, which includes quality information. Any information related to quality can help planners to improve the quality of a plan. BIM-based quality information management makes BIM a quality information repository. The information requirements of the LPS can be fulfilled by BIM.

The Interviewee 8 discussed the quality information storage and presentation in BIM, as evidenced in the following statement:

[...] According to the results of BIM-based plan simulation and optimisation, the constraints are detected in look-ahead plan. The information of material constraints, technique constraints and manpower constraints could be intuitively presented and recorded in the BIM. The work areas which are assumed to have constraints have been highlighted in orange. These constraints in orange zones need to be solved before construction. After constraints are removed, the package colour could be changed to green. Because of the striking colour reminder, it is easy to recognise unsolved constraints, which is also easier for planners to control overall plan [...] -Interviewee 8

#### **5.3.2.4 Visual management - BIM-based dynamic template display**

Template display is one of the approaches in visual management; it is not a new approach. BIM-based dynamic template display adopts BIM as an information carrier to display information dynamically. It was described by Interviewee 13 that,

[...] Standard construction product samples could be described through a partial perspective in a 3D BIM model, which could be zoomed in and out.

Work process is displayed dynamically in the virtual BIM environment  
[...]-Interviewee 13

More than half of the interviewees highlighted that BIM contained work plans and site layout information and that it can display this information intuitively. From a visual point of view, BIM can replace the function of conventional visual information templates.

#### **5.3.2.5 5S management - BIM-based visual construction layout**

The vast majority of the interviewees (20 of 22) confirmed the positive interaction between 5S management and BIM-based visual construction layout. According to Interviewee 3,

[...] The first two S's in 5S management are sorting and simplifying, which aim to make construction sites orderly and neat. The visual-based construction layout in BIM could also provide similar function [...]-  
Interviewee 3

Interviewee 9 further added,

[...] The building materials and facilities are stored by type, size and material grade with clear boundary identifications in BIM-based visual construction layout. The implementation of 5S management can be facilitated by BIM [...]-  
Interviewee 9

#### **5.3.2.6 Kanban - BIM-based information management**

16 of 22 (77%) interviewees agreed that kanban benefits from the application of BIM-based information management. This was explained by Interviewee 10:

[...] Kanban, the carrier of information, is used to convey information and issue instructions. The relevant construction information of the current construction stage and the instructions from the next construction stage are

provided from the BIM model through BIM-based information management  
[...] - Interviewee 10

Some of the interviewees (4 of 22) argued that a functional overlap exists between kanban and BIM in terms of quality information transmission. A representative view of all interviewees' replay was stated by Interviewee 9:

[...] Compared with BIM, paper-based Kanban is cheaper. In addition, Kanban is easier to operate and the information it carries can meet the needs [...] - Interviewee 9

#### **5.3.2.7 Kanban - BIM-based quality inspection**

The majority of the interviewees (19 of 22) agreed that a positive interaction exists between kanban and BIM-based quality inspection. The integrated implementation of kanban and BIM-based quality inspection was explained by Interviewee 17:

[...] In terms of quality, the construction of Kanban requires the quality of the current stage to meet the quality requirements of the next stage. BIM-based quality inspection enhances workers' ability to detect quality defects. The quality defects are efficiently prevented to pass to the next construction stage through integrating Kanban and BIM-based quality inspection [...] - Interviewee 17

#### **5.3.2.8 Standardisation - BIM-based dynamic template display**

The benefits of BIM-based dynamic template display in standardisation were widely accepted by all interviewees (22 of 22). According to Interviewee 14,

[...] Because the mobility of construction site workers is tremendous, a strict construction standard regulation is required to improve construction standardisation. BIM-based dynamic template display provides standard construction regulation with a way to visualise work procedure and work technology [...] - Interviewee 14

Furthermore, Interviewee 16 added,

[...] The workers' understandings of building techniques are improved through demonstrating construction work samples in BIM, which helps to achieve construction standardisation [...] -Interviewee 16

#### **5.3.2.9 Standardisation - BIM-based quality information management**

18 of 22 (82%) interviewees supported the benefits of integrating standardisation and BIM-based quality information management. The interaction between the two concepts was further explained by Interviewee 20:

[...] Standardisation is carried out under the principle of continuous improvement. BIM-based information management provides information support for continuous improvement. The standard regulations are continuously updated with the accumulation of construction data and experience [...] -Interviewee 20

#### **5.3.2.10 First run study-BIM-based construction plan simulation and optimisation**

All interviewees made it clear that there is a positive relationship between a first-run study and BIM-based construction plan simulation and optimisation. According to Interviewees 2 and 5, first-run studies and BIM-based construction plan simulation and optimisation are similar as they both require the repeated verification of plans. During the planning process, BIM constantly simulates and optimises the construction plan in a virtual environment. The key points of quality control can be set, and the weaknesses of the plan are identified through BIM simulation and optimisation. Interviewee 1 summarised that the first run study advocates optimising the plan through concept level and BIM provides a detailed simulation and optimisation tool

#### **5.3.2.11 Concurrent engineering - BIM-based clash detection**

The interaction between concurrent engineering and BIM-based clash detection was

confirmed by all interviewees. The function of concurrent engineering was mentioned by Interviewee 7 as,

[...] The concurrent engineering requires the participants to join the design as soon as possible in order to improve the constructability of the design and reduce errors in the construction process [...] -Interviewee 7

Interviewees explained the role of BIM in concurrent engineering that ‘BIM-based clash detection is a valuable application to prevent design drawing defects before construction. Their integrated application could be a kind of proactive quality defect prevention approach

#### 5.4 Discussion of Findings from Survey

The interview results are listed in Table 27 and Table 28. 17 quality-based strategical interactions and 11 implementation interactions are identified from interviews. These findings proved a solid foundation to develop an interaction framework.

Table 27: The Quality-based Strategical Interactions between Lean Construction Theories and BIM Mechanisms

No.	The quality-based strategical interactions	Agreement level	Literature review	Survey
1	Proactive quality defect prevention culture -Visualisation	18 of 22		x
2	Proactive quality defect prevention culture - Simulation and calculation	22 of 22		x
3	Conversion to a quality-based mindset - Visualisation	13 of 22		x
4	Conversion to a quality-based mindset - Simulation and calculation	15 of 22		x
5	Conversion to a quality-based mindset - Collaboration	15 of 22		x
6	Decentralised control- giving authority to worker-Visualisation	21 of 22		x
7	Decentralised control-giving authority to worker -Simulation and calculation	22 of 22		x
8	Decentralised control-giving authority to worker- Dynamic	20 of 22		x
9	Decentralised control- giving	22 of 22		x

10	authority to worker- Integration Customer quality requirements – Dynamic	21 of 22	x
11	Customer quality requirement – Collaboration	22 of 22	x
12	Customer quality requirements – Coherence	19 of 22	x
13	Pull-based quality management – Visualisation	19 of 22	x
14	Pull-based quality management – Collaboration	18 of 22	x
15	Pull-based quality management – Integration	22 of 22	x
16	Continuous quality improvement – Dynamic	17 of 22	x
17	Cooperation and communication – Collaboration	22 of 22	x

Table 28: The Quality-based Implementation Interactions between Lean Construction Techniques and BIM Applications

No.	The quality-based implementation interactions	Agreement level	Literature review	Survey
1	Last planner system-BIM-based design joint inspection and technical disclosure	22 of 22		x
2	Last planner system-BIM-based construction plan simulation and optimisation	22 of 22	x	x
3	Last planner system-BIM-based quality information management	21 of 22	x	x
4	Visual management-BIM-based dynamic template display	20 of 22		x
5	5S management-BIM-based visual construction layout	20 of 22		x
6	Kanban-BIM-based information management	16 of 22	x	x
7	Kanban-BIM-based quality inspection	19 of 22		x
8	Standardisation-BIM-based dynamic template display	22 of 22		x
9	Standardisation-BIM-based quality information management	18 of 22		x
10	First run study-BIM-based construction plan simulation and optimisation	22 of 22		x
11	Concurrent engineering-BIM-based clash detection	22 of 22		x

Using the results of the interviews, the interactions between lean construction and BIM from a quality improvement perspective are summarised. There were 17 quality-based strategical interactions and 11 quality-based implementation interactions identified in total. Some interactions were validated by the existing literature (See Table 31), such as the LPS and BIM-based quality information management (Shi, 2015), the LPS and BIM-based construction plan simulation and optimisation (Liu and Shi, 2017), kanban and BIM-based information management (*ibid.*). Most interactions were supported by an overwhelming majority of interviewees. However, there were still some interactions that were not widely recognised, and some were even disputed by the interviewees. These interactions are the focus of the discussion in this chapter.

As shown in Table 27, quality-based strategical interactions 3, 4 and 5 were not supported by an overwhelming majority of interviewees, and these interactions were even rejected by some interviewees. These three interactions are all related to the quality-based lean construction theory of conversion to a quality-based mindset. Quality-based theoretical interactions are related to quality awareness, and some interviewees did not think that tools can help change mindsets. As Zhou (2017) states, quality awareness is a rational cognition that consists of quality cognition, quality belief and quality knowledge. Quality cognition is the understanding of the quality attributes of construction products, which mainly refers to recognising the quality characteristics of construction products and the importance of construction product quality. Quality belief refers to a feeling for product quality which can encourage workers to meet quality requirements. Quality knowledge refers to the essential knowledge needed to provide high-quality construction products, such as reasonable construction techniques and quality management knowledge. Furthermore, quality cognition is the basis of quality awareness. According to the explanation of quality awareness, quality cognition and quality knowledge can influence the conversion to a quality-based mindset. The visualisation mechanism of BIM provides an intuitive approach to viewing the final construction product, which helps workers to understand the quality attributes of a construction product before they start work. The simulation and calculation mechanism of BIM provides an approach to virtual construction, which

helps workers develop a thorough understanding of construction technology. Workers' quality knowledge is enhanced by BIM. The collaboration mechanism of BIM allows workers to know the importance of their work through communication, which is enhanced by the workers' quality cognition. Generally, the BIM mechanisms of visualisation, simulation and calculation and collaboration are helpful for improving workers' quality cognition and knowledge. As such, these mechanisms can be identified as playing a positive role in quality-based mindset conversion. Therefore, these interactions are accepted in this study.

As presented in Table 28, quality-based implementation interactions 6 were not supported by an overwhelming majority of interviewees. Some interviewees believe there exists a repetitive function between kanban and BIM-based information management. Additionally, they also think paper-based kanban boards are cheap and easy to use. It is interesting that the views of the interviewees were different from those found in the literature review. According to Liu and Shi (2017), BIM provides the related quality information to support the implementation of kanban. Although kanban boards can provide the necessary quality information, this information is not intuitive or rich enough. It is difficult for workers to develop a comprehensive understanding of their work through kanban boards. BIM is a much more powerful information carrier than the information boards used in conventional kanban. BIM stores various construction information and the information is easy to retrieve (Eastman et al., 2011). Moreover, the excessive use of paper-based kanban boards can lead to waste. In general, BIM, as an information carrier, can take the place of traditional paper-based kanban boards. Nevertheless, the implementation of BIM should follow the kanban system. As such, the interaction between kanban and BIM-based information management remains positive in this study. Generally, all the quality-based implementation interactions between lean construction techniques and BIM applications are accepted. These interactions have more applications, which are discussed in the next section.

## **5.5 Summary**

According to the results of interviews, there were 17 interactions between quality-



based lean construction theories and quality-based BIM mechanisms, and 11 interactions between quality-based lean construction techniques and quality-based BIM applications were identified. They were divided into two parts according to their characteristics: one is strategic interactions; the other is implementation interactions. This chapter provides a foundation for further develops these interactions into a two levels interaction framework.

## **Chapter 6 Discussion and Framework Development**

### **6.1 Introduction**

This chapter presents the process of discussing and developing and validating the quality-based lean and BIM interaction framework. This framework was based on findings from the literature review (Chapter 2), case studies (Chapter 4) and interviews (Chapter 5). A new paradigm was proposed and recommended for Chinese construction industry to improve quality through analysing interaction framework.

### **6.1 Quality-based Lean Construction and BIM Interaction Framework Discussion and Development**

According to the research result of survey, there were 17 quality-based strategical interactions and 11 implementation interactions were identified. These quality-based interactions contribute to the knowledge of lean construction and BIM. The result of survey encourage researcher to use a concise way to present the interactions. This research on presenting the results of investigating interactions between lean construction and BIM to improve Chinese construction quality was inspired by the research framework of Sacks et al. According to Sacks et al. (2010), lean principles and BIM functions were arranged in a matrix. The interaction points between lean construction and BIM were presented in a bare matrix. Their framework, seen in Table 29, was adopted as a reference template for building a new research framework which can be used to investigate the interactions between lean construction and BIM to improve the quality of Chinese construction in construction phase.

According to findings of survey, interaction framework was conducted in two aspects. One was conducted between quality-based lean construction theories and quality-based BIM mechanisms, and the other was between quality-based lean construction techniques and quality-based BIM applications. Due to this research intended to present these interactions in a concise and easy way which help reader to understand, Sacks et al. (2010)' framework were adopted to present research results. This new framework was expected to inspire future researches on improving Chinese construction quality from the perspective of integrating lean construction and BIM. There are two levels in this framework, which are strategical level and implementation level. The strategical level framework emphasises on illustrating the interactions

between quality-based lean construction theories and quality-based BIM mechanisms. In the strategical level, all quality-based lean construction theories were juxtaposed in a row, and the quality-based BIM mechanisms were juxtaposed in a column of matrix (see Table 30). The interactions on strategical level were listed in each cell in matrix. The brief explanations of each cell content were provided in explanation table (see Table 31). The framework in implementation level was same with strategical level framework. The quality-based lean construction techniques and quality-based BIM applications were juxtaposed in matrix and the interactions on implementation level were presented in each cell in matrix (see Table 32). The cell contents were provided in the explanation table (see Table 33).

Table 29: Interaction Matrix of Lean Principles and BIM Functionalities (Sacks et al., 2010)

BIM functionality	Lean principles																																	
	Reduce variability		Reduce cycle times		Reduce batch sizes		Increase flexibility		Select an appropriate production control approach		Standardize		Institute continuous improvement		Use visual management		Design the production system for flow and value				Ensure comprehensive requirements capture		Focus on concept selection		Ensure requirements flow down		Verify and validate		Go and see for yourself		Decide by consensus consider all options		Cultivate an extended network of partners	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X										
Visualization of form	1	1,2												3				4			11			5			6			4				
Rapid generation of design alternatives	2	1		22								7	7		8																			
Reuse of model data for predictive analyses	3	9	9	22			51											1	16		5													
	4		10		12										8				16		5													
	5	1,2	1	12														1	1	1	5													
Maintenance of information and design model integrity	6	11	11																	11														
	7	12	12	22																	12													
Automated generation of drawings and documents	8	11		22 (52)		53									54 54																			
Collaboration in design and construction	9		23					36						36																				
	10	2,13		24				33										43		56	46			49										
Rapid generation and evaluation of multiple	11	14	25 (29)			31								(41)																				
construction plan alternatives	12		15	25 (29)					37						(41)				44		47													
	13	2	40	25 (29)						17			40	40	40						47			49										
Online/ electronic object-based communication	14		29	26	30	30		34					34	(42)							47		48											
	15	18		26	30	30		34		38			38	34	(42)				45					49										
	16	19	27				32																											
	17		20	28				35							(42)																50			
	18		21		30	30		34			39				(42)						47		48											

This two-level interaction framework could provide strategical guidance for companies that intend to integrate lean construction and BIM to improve construction quality. The implementation level framework provides a way to view the potential interactions between quality-based lean construction techniques and quality-based BIM applications. This level framework provides specific implementation guidelines. It is used to illustrate how to improve the quality of buildings by combining existing lean construction techniques with BIM applications.

This framework was originated from the results of the literature review and finding from case studies and interviews. The strategical level framework was presented in Table 33 and Table 34, and the implementation level framework was illustrated in Table 35 and Table 36. The framework will be challenged, validated and enhanced by interviewing Chinese construction experts, as presented in the next section.

Table 30: Strategic Interaction Matrix of Quality-based Lean Construction Theories and Quality-based BIM Mechanisms

		Quality-based lean construction theories						
		Proactive quality defect prevention culture	Conversion to a quality-based mindset	Decentralised control- giving authority to workers	Customer quality requirements	Pull-based quality management	Continuous quality improvement	Cooperation and communication
		1	2	3	4	5	6	7
Quality-based BIM Mechanisms								
Visualization	a	x	x	x		x		
Simulation and calculation	b	x	x	x				
Dynamic	c			x	x		x	
Collaboration	d		x		x	x		x
Integration	e			x		x		
Coherence	f				x			

Table 31: Strategic Interaction Matrix: Explanations of Cell Contents

Index	Explanation
1-a	The visualisation mechanism of BIM utilises people's visual perceptions to detect defects in a virtual environment. Quality problems can be actively resolved before actual construction begins. Quality is ensured through a proactive prevention approach.
1-b	The simulation and calculation mechanism of BIM helps planners to make reasonable plans. A good construction plan can prevent many quality defects from occurring. Moreover, construction personnel can fully understand the design intent and construction plan before construction using BIM simulation and roaming.
2-a	Visual BIM can improve the workers' quality cognition by allowing them to intuitively view the final construction product. A quality-based mindset can be created through the promotion of quality awareness
2-b	The BIM mechanism of simulation and calculation enhances the quality knowledge of workers by showing them construction techniques in a virtual construction environment. Quality awareness is promoted through BIM simulation, which leads to changes in mindsets
2-d	The BIM mechanism of collaboration helps to promote workers' quality cognition, which leads to the promotion of quality awareness. A quality-based mindset will also gradually take shape as a result
3-a	BIM provides a simple and direct expression of information through a visualised model. It is beneficial for workers in understanding inspection content quickly and accurately after the authority of quality control is given to them
3-b	A mechanism of simulation and calculation enables BIM to provide a way to verify workers' opinions in the process of planning. This ensures the quality of a plan after last planners are involved
3-c	The dynamic mechanism enables BIM to transmit up-to-date quality information from the construction site to the office. Managers can identify the latest construction quality trends in a timely manner. This makes decentralised management more reliable
3-e	BIM is a platform which can integrate other advanced technologies to promote the ability of quality inspection. The application of BIM improves the quality of workers' inspections
4-c	BIM can provide customers with the latest construction information continuously and steadily so that they can make a more accurate judgment of a construction site in order to put forward their quality requirements
4-d	BIM provides a collaboration platform that facilitates quality requirement communication between constructors and customers. The information can be transmitted on this platform without hindrance
4-f	Coherence mechanisms make BIM adaptable to design changes and facilitate a rapid response to customer quality requirements
5-a	The visualisation of BIM provides support for the intuitive representation of quality requirements, which is convenient for

- workers to understand
- 5-d BIM can provide a collaboration platform for workers in consecutive construction stages. The quality requirements of the next construction stage are transmitted through the BIM platform
  - 5-e BIM can improve quality inspection abilities by integrating advanced technologies. Quality inspection is carried out from the back to forward between consecutive processes by pulling quality. BIM enhances the implementation of pull-based quality management
  - 6-c BIM is a tool for constantly collecting, processing and storing information. Managers can learn from the lessons and experiences of past projects through the information stored in BIM. Then, the goal of continuous quality improvement can be achieved
  - 7-d Information is transmitted in BIM without hindrance, which increases the efficiency of cooperation. Moreover, the stability of information transmission strengthens cooperation
-



Table 32: Implementation Interaction Matrix of Quality-based Lean Construction Techniques and Quality-based BIM Applications

		Quality-based lean construction techniques						
		Last planner system	Visual management	5S management	Kanban	Standardisation	First run study	Concurrent engineering
		1)	2)	3)	4)	5)	6)	7)
Quality-based BIM applications								
BIM-based clash detection	I							X
BIM-based design joint inspection and technical disclosure	II	X						
BIM-based construction plan simulation and optimisation	III	X					X	
BIM-based design change management	IV							
BIM-based dynamic template display	V		X			X		
BIM-based visual construction layout	VI			X				
BIM-based quality information management	VII	X			X	X		
BIM-based quality inspection	VIII				X			

Table 33: Implementation Interaction Matrix: Explanations of Cell Contents

Index	Explanation
1)- II	The quality of plans benefits from BIM as joint design inspection, and technical explanation is conducted in a virtual 3D environment. The visualisation of BIM helps planners to understand design intent and facilitates communication and inspection in the design joint inspection phase
1)- III	4D BIM simulation and calculation provide a complete construction procedure in the virtual environment to the planner. The planner can view the plan result intuitively, which makes planner easy to plan
1)-VII	BIM-based quality information management makes BIM a quality information repository. The information requirements of the LPS can be fulfilled by BIM
2)- V	The construction control points, the dynamic construction model, the important construction joints and the construction techniques can be magnified and presented through dynamic templates. Additionally, as BIM-based dynamic templates are easy to make and modify, the implementation of visual management is simplified by adopting the BIM template
3)- VI	BIM can improve the quality of 5S management by providing a visual-based construction layout approach. Temporary storage areas and construction tool placement points can be set up by 5S management with clear boundaries through a BIM-based visual construction layout
4)-VIII	BIM, as an information carrier, can transfer information between consecutive construction stages. The requirements of transmitting quality acceptance standards and construction information are fulfilled by BIM
4)-VIII	BIM-based quality inspection enhances workers' ability to detect quality defects. The quality defects can be efficiently prevented from passing to the next construction stage by integrating kanban and BIM-based quality inspection
5)- V	BIM-based dynamic template display presents construction standard regulations through visualised work procedures and virtual standard templates. The workers' understanding of construction techniques and procedures is improved through demonstrating construction work templates in BIM, which helps to achieve construction standardisation
5)-VII	BIM-based information management provides information support for continuous improvement. The standard regulations are continuously updated with the accumulation of construction data and experience
6)- III	The aims of a first-run study are achieved through BIM-based construction plan simulation and optimisation. BIM is a good tool for constantly simulating and optimising a construction plan in a virtual environment, which can facilitate the implementation of a first-run study
7)- I	Concurrent engineering requires the participants to join the design stage as early as possible to improve the constructability of the design

and to reduce errors in the construction process. BIM-based clash detection can automatically detect design defects. Its application brings convenience to concurrent engineering.

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## **6.2 Quality-based Lean Construction and BIM Interaction Framework Validation**

### **6.2.1 Framework validation process**

The aim of the quality-based lean construction and BIM interaction framework validation was to refine and examine the appropriateness of the framework. This was achieved by interviewing 10 Chinese construction experts based in China. These interviewees were not working in the case study and interview companies. Therefore, they did not have any previous knowledge of this study. The interviewees were asked to give qualitative insights into the quality-based lean construction and BIM interaction framework. The framework structure and content were expected to be verified in this process. The interviewee feedback provides an opportunity to test the accuracy and completeness of the research outcome.

There were ten interviewees involved in the interaction framework validation process (see Table 34). All of the interviewees had more than ten years of experience in construction quality management. Furthermore, five interviewees had more than three years of experience in both lean construction and BIM implementation. Two of the interviewees had at least four years of lean construction implementation experience, and they were making endeavours to involve BIM in their projects. Three interviewees had had more than five years of experience in the field of BIM implementation. The integrated application of BIM and lean construction was their current focus. The framework was shown to each interviewee, and this formed the basis of the discussions.

Table 34: Interviewees in Framework Validation

<b>Name</b>	<b>Designation</b>	<b>Lean construction and BIM Application experience (years)</b>
1	Project Manager	More than 3 (Lean+BIM)
2	Project Manager	More than 5 (BIM)
3	Deputy Project Manager	More than 4 (Lean)
4	Project Manager	More than 3 (Lean+BIM)
5	Technical Director	More than 4 (Lean)
6	Vice-technical Director	More than 5 (BIM)
7	Deputy Project Manager	More than 3 (Lean+BIM)
8	Deputy Construction Manager	More than 3 (Lean+BIM)
9	Project Manager	More than 5 (BIM)
10	Project Manager	More than 3 (Lean+BIM)

## 6.2.2 Results of quality-based lean construction and BIM interaction framework validation interviews

### 6.2.2.1 Clarity of the quality-based lean construction and BIM interaction framework structure

All of the interviewees agreed that both levels of interaction frameworks had a clear structure. In the theoretical interaction matrix, quality-based lean construction theories and quality-based BIM mechanisms were arranged in a matrix. The interaction points between quality-based lean construction theories and quality-based BIM mechanisms are presented in the bare matrix. The implementation interaction matrix also adopted this structure. This structure can present interactions in a simple and intuitive way. According to Interviewee 5,

[...] This structure is without a doubt successful. It is easy to know what this framework is for. The interaction points are obviously presented in the matrix  
[...]-Interviewee 5

In addition, nearly all interviewees (9 out of 10) expressed an appreciation of the simplicity presented by the explanation table of the interaction matrix. For example, Interviewee 6 explained that,

[...] Things that can be solved with simple tables should not be so complicated.

Theses tables meet the needs of the framework for explanation [...]-  
Interviewee 6

However, some interviewees gave suggestions on adjusting the framework to make it easier to read. This is further discussed in the next section for improving the framework.

#### **6.2.2.2 Appropriateness of quality-based lean construction and BIM interaction framework content**

All interviewees agreed that the terms adopted in the strategic interaction framework and implementation interaction framework were appropriate and worked well for these frameworks. In addition, they also pointed out that the cell contents in the interaction matrixes were briefly described well. They all agreed that the content of the quality-based lean construction and BIM interaction frameworks was readable and reasonable.

#### **6.2.2.3 Recommendations for improving quality-based lean construction and BIM interaction framework**

The interviewees recommended enhancing the connection between the matrix and the explanation table. The symbol used to express interaction is ‘X’, which is not easy to correspond with the explanation table. They suggested replacing ‘X’ with numerical symbols, such as ‘①’ and ‘(1)’ for the two levels. In addition, the arrangement of these numerical symbols should be consistent with the order in which people read. The validated strategic interaction matrix and the validated strategic interaction explanation table are presented in Table 35 and Table 36. The validated implementation interaction matrix and validated implementation interaction explanation table are presented in Table 37 and Table 38.

Table 35: Validated Strategic Interaction Matrix of Quality-based Lean Construction Theories and Quality-based BIM Mechanisms

		Quality-based lean construction theories						
		Proactive quality defect prevention culture	Conversion to a quality-based mindset	Decentralised control- giving authority to workers	Customer quality requirements	Pull-based quality management	Continuous quality improvement	Cooperation and communication
Quality-based BIM mechanisms		1	2	3	4	5	6	7
Visualization	a	①	②	③		④		
Simulation and calculation	b	⑤	⑥	⑦				
Dynamic	c			⑧	⑨		⑩	
Collaboration	d		⑪		⑫	⑬		⑭
Integration	e			⑮		⑯		
Coherence	f				⑰			

Table 36: Validated Strategic Interaction Matrix: Explanations of Cell Contents

Index	Explanation
①	The visualisation mechanism of BIM utilises people's visual perceptions to detect defects in a virtual environment. Quality problems can be actively resolved before actual construction begins. Quality is ensured through a proactive prevention approach.
②	Visual BIM can improve the workers' quality cognition by allowing them to intuitively view the final construction product. A quality-based mindset can be created through the promotion of quality awareness
③	BIM provides a simple and direct expression of information through a visualised model. It is beneficial for workers in understanding inspection content quickly and accurately after the authority of quality control is given to them
④	The visualisation of BIM provides support for the intuitive representation of quality requirements, which is convenient for workers to understand
⑤	The simulation and calculation mechanism of BIM helps planners to make reasonable plans. A good construction plan can prevent many quality defects from occurring. Moreover, construction personnel can fully understand the design intent and construction plan before construction using BIM simulation and roaming.
⑥	The BIM mechanism of simulation and calculation enhances the quality knowledge of workers by showing them construction techniques in a virtual construction environment. Quality awareness is promoted through BIM simulation, which leads to changes in mindsets
⑦	A mechanism of simulation and calculation enables BIM to provide a way to verify workers' opinions in the process of planning. This ensures the quality of a plan after last planners are involved
⑧	The dynamic mechanism enables BIM to transmit up-to-date quality information from the construction site to the office. Managers can identify the latest construction quality trends in a timely manner. This makes decentralised management more reliable
⑨	BIM can provide customers with the latest construction information continuously and steadily so that they can make a more accurate judgment of a construction site in order to put forward their quality requirements
⑩	BIM is a tool for constantly collecting, processing and storing information. Managers can learn from the lessons and experiences of past projects through the information stored in BIM. Then, the goal of continuous quality improvement can be achieved
⑪	The BIM mechanism of collaboration helps to promote workers' quality cognition, which leads to the promotion of quality awareness. A quality-based mindset will also gradually take shape as a result
⑫	BIM provides a collaboration platform that facilitates quality requirement communication between constructors and customers. The information can be transmitted on this platform without hindrance

- ⑬ BIM can provide a collaboration platform for workers in consecutive construction stages. The quality requirements of the next construction stage are transmitted through the BIM platform
  - ⑭ Information is transmitted in BIM without hindrance, which increases the efficiency of cooperation. Moreover, the stability of information transmission strengthens cooperation
  - ⑮ BIM is a platform which can integrate other advanced technologies to promote the ability of quality inspection. The application of BIM improves the quality of workers' inspections
  - ⑯ BIM can improve quality inspection abilities by integrating advanced technologies. Quality inspection is carried out from the back to forward between consecutive processes by pulling quality. BIM enhances the implementation of pull-based quality management
  - ⑰ Coherence mechanisms make BIM adaptable to design changes and facilitate a rapid response to customer quality requirements
-



Table 37: Validated Implementation Interaction Matrix of Quality-based Lean Construction Techniques and Quality-based BIM Applications

		Quality-based lean construction techniques						
		Last planner system	Visual management	5S management	Kanban	Standardisation	First run study	Concurrent engineering
Quality-based BIM applications		1)	2)	3)	4)	5)	6)	7)
BIM-based clash detection	I							(1)
BIM-based design joint inspection and technical disclosure	II	(2)						
BIM-based construction plan simulation and optimisation	III	(3)					(4)	
BIM-based design change management	IV							
BIM-based dynamic template display	V		(5)			(6)		
BIM-based visual construction layout	VI			(7)				
BIM-based quality information management	VII	(8)			(9)	(10)		
BIM-based quality inspection	VIII				(11)			

Table 38: Validated Implementation Interaction Matrix: Explanations of Cell Contents

<b>Index</b>	<b>Explanation</b>
(1)	Concurrent engineering requires the participants to join the design stage as early as possible to improve the constructability of the design and to reduce errors in the construction process. BIM-based clash detection can automatically detect design defects. Its application brings convenience to concurrent engineering
(2)	The quality of plans benefits from BIM as joint design inspection, and technical explanation is conducted in a virtual 3D environment. The visualisation of BIM helps planners to understand design intent and facilitates communication and inspection in the design joint inspection phase
(3)	4D BIM simulation and calculation provide a complete construction procedure in the virtual environment to the planner. The planner can view the plan result intuitively, which makes planner easy to plan
(4)	The aims of a first-run study are achieved through BIM-based construction plan simulation and optimisation. BIM is a good tool for constantly simulating and optimising a construction plan in a virtual environment, which can facilitate the implementation of a first-run study
(5)	The construction control points, the dynamic construction model, the important construction joints and the construction techniques can be magnified and presented through dynamic templates. Additionally, as BIM-based dynamic templates are easy to make and modify, the implementation of visual management is simplified by adopting the BIM template
(6)	BIM-based dynamic template display presents construction standard regulations through visualised work procedures and virtual standard templates. The workers' understanding of construction techniques and procedures is improved through demonstrating construction work templates in BIM, which helps to achieve construction standardisation
(7)	BIM can improve the quality of 5S management by providing a visual-based construction layout approach. Temporary storage areas and construction tool placement points can be set up by 5S management with clear boundaries through a BIM-based visual construction layout
(8)	BIM-based quality information management makes BIM a quality information repository. The information requirements of the LPS can be fulfilled by BIM
(9)	BIM, as an information carrier, can transfer information between consecutive construction stages. The requirements of transmitting quality acceptance standards and construction information are fulfilled by BIM
(10)	BIM-based information management provides information support for continuous improvement. The standard regulations are continuously updated with the accumulation of construction data and experience
(11)	BIM-based quality inspection enhances workers' ability to detect

quality defects. The quality defects can be efficiently prevented from passing to the next construction stage by integrating kanban and BIM-based quality inspection

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### **6.3 Interaction Framework Implementation Strategy**

Reviewing the matrixes in the two-level interaction framework reveals several interesting trends related to integrating the use of lean construction and BIM to improve construction quality. The integration focuses were also recommended through the analysing framework.

In the strategic interaction matrix, the highest concentration of the quality-based lean construction theory is ‘decentralising controls -give authority to workers’, followed by ‘quality-based mindset conversion’, ‘customer quality requirements’ and ‘pull-based quality management’. These have significantly more interactions than any other theories. There are more options for these lean construction theories to integrate BIM to improve construction quality. Meanwhile, the BIM mechanisms of ‘visualisation’ and ‘collaboration’ have the most interactions with lean construction theory. In addition, these two mechanisms have interactions with three of the four highest concentration lean construction theories. It is possible to speculate that the interactions between the lean construction theories of ‘decentralised controls- giving authority to workers’, ‘quality-based mindset conversion’, ‘pull-based quality management’ and the BIM mechanisms of ‘visualisation’ and ‘collaboration’ should be focused if construction companies want to integrate lean construction and BIM to improve construction quality. These interactions should be the key to the strategical success of quality-based integration.

According to the implementation interaction matrix analysis results, the highest concentration quality-based lean construction technique is ‘the last planner system’. Meanwhile, BIM-based quality information management has the highest concentrations of unique interactions in the implementation matrix. Therefore, these two approaches of ‘the last planner system’ and ‘BIM-based quality information management’ should be primarily considered in the project. These should be the key

to the implementational success of quality-based integration.

Although the interactions in quality-based interaction framework are clear, it should not lead readers to assume that their achievements in practice are straightforward. Much previous experience represented that the benefit of implementing information technology in construction management cannot be taken for granted (Sacks et al., 2010). The key to integrating lean construction and BIM to improve construction quality are environment changing and the process changing. The environment changing mainly focuses on building a quality-based construction culture. A good quality-based construction culture is the basis of integrating lean construction and BIM to improve construction quality. It helps to facilitate any construction quality improvement activities in a project. The process changing refers to change conventional construction process to fit lean construction and BIM implementation. Lean construction theories and techniques could be referred to build a reasonable process for better results. These measures are prerequisites for the functioning of this framework.

Another interesting finding has been obtained by interpreting the interaction matrix. The strategic matrix shows that each quality-based BIM mechanism supports multiple quality-based lean constructions, whereas a single quality-based lean construction theory can guide the application of multiple quality-based BIM mechanisms. The relationships in the implementation matrix are the same. This result shows that the quality-based lean construction and BIM interactions should be synergistically utilised rather than adopting point-to-point utilisation. A broader view is necessary to conduct integrations between lean, BIM and quality.

With the development of information technology and the maturity of lean construction concepts, the synergy between them is likely to become increasingly prominent. The quality-based interactions between lean construction and BIM should be seen as a whole rather than the sum of the isolated parts. Due to the strong interaction and synergy between BIM and lean construction in quality improvement, the synergistic effect should be carefully considered. In order to present the whole relationship more

vividly, an ‘LC-BIM quality improvement house’ is showed in Figure 5. There are four important elements in the ‘LC-BIM quality improvement house’, which are ‘roof’, ‘column’, ‘beam’, ‘core heating system’ and ‘foundation’. The function of this house is to provide a holistic view of quality-based synergies between lean construction and BIM. Poor construction quality is likened to cold air in winter. The people (refer to construction company) is needed to be defended themselves against cold air (poor construction quality) to keep warm (prevent poor construction quality). Therefore, people need to build a house to keep warm.

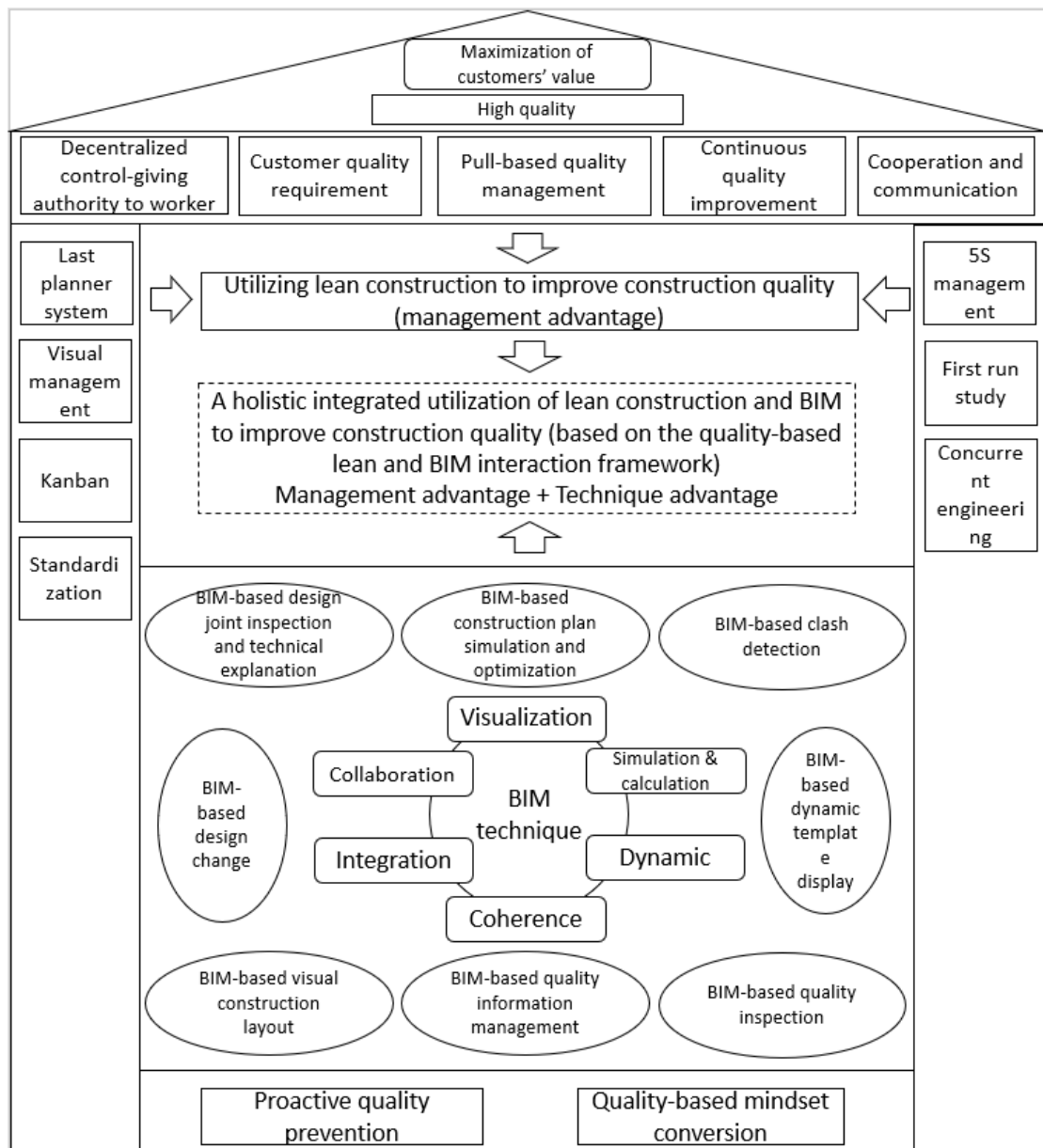


Figure 5: LC-BIM Quality Improvement House

According to the importance of environment changing and process changing in integrating lean construction and BIM to improve construction quality, the 'Proactive quality defect prevention culture' and 'quality-based mindset conversion' are located in the 'foundation', which means that they are the basis for the successful implementation of lean construction and BIM for improving construction quality. Both should be achieved at the beginning of the project.

The importance of process changing directs the rest of lean construction theories and lean construction techniques to be beam and column respectively. This because the lean construction theories and techniques are referred to build a reasonable process for better results. The new process is the pillar of the whole integration which supports all integration implementation.

Customer value maximisation is at the top of the 'LC-BIM quality improvement house' as its roof, indicating that the highest goal of integrating lean construction management and BIM is to maximise customer value. The 'highest quality' element can be classified under customer requirements, which means that customer value can be increased through providing high-quality construction products.

Through previous measures, the house is built. However, the people still feel cold if they have not got any heating system in the house. BIM is the heating system in this house which the mechanisms and applications of BIM could facilitate lean construction application and improve its effects. BIM is a platform to achieve quality-based lean construction theories and techniques. Lean construction is the catalyst to facilitate and direct BIM application. They complement each other to keep people warm (help construction company to prevent poor construction quality). The whole view of integrating lean construction and BIM to improve construction quality is achieved. The best practical result is not achieved by any single interactions, but to synergistically utilised these interactions. Due to the strong interaction and synergy between BIM and lean construction in quality improvement, the holistically integrated

utilisation of interactions between lean construction and BIM in the framework should be a new paradigm for China to improve its construction quality.

#### **6.4 Summary**

The development and validation process of proposed quality-based lean and BIM interaction framework are presented in this section. 17 quality-based strategical interactions and 11 implementation interactions are listed in two-level interaction matrix. These two matrix and explanation tables consist the two-level interaction frameworks. The detail interactions are presented in a concise and easy way which help reader to understand. The interaction framework is the core of this research. This framework is created based on case study and survey results. The quality-based interactions between lean construction and BIM are firstly detail discussed in this research. This new framework was expected to inspire future researches on improving Chinese construction quality from the perspective of integrating lean construction and BIM. The framework contributes to a new way of analysing interactions between quality-based lean construction and quality-based BIM.

In Section 6.2, the validity of the framework is analysed and verified in this section. The validation process was conducted among 10 Chinese experts. It improved the framework content presentation. The framework became more concise and understandable.

The interaction framework implementation strategy had been discussed in this section. The analysing of two-level quality-based framework results the most important interactions and these interactions should be carefully considered in the practical implementation. The synergy between quality-based interactions is prominent. A vivid presentation of the whole relationships resulted in a 'LC-BIM quality improvement house'. This section contributes to facilitates other researchers to understand the integrated implementation of lean construction and BIM to improve construction quality in a holistic view. According to the analysing of the framework, the holistically integrated utilisation of interactions between lean construction and BIM in the framework should be a new paradigm for China to improve its construction quality.

Generally, this chapter is the core of whole thesis. It is the results after discussing findings from literature review, case studies and surveys. The results of this chapter fulfils the gap of researching on the quality-based interactions between lean construction and BIM.



## **Chapter 7: Conclusion**

### **7.1 Introduction**

The conclusions drawn from the research findings are outlined in this chapter. The first section presents the research achievements based on the research aim and objectives. The second section discusses the main research contribution of this study. The research limitations are discussed in the third section and recommendations for further research are also provided.

### **7.2 Achievement of the Research Aim and Objectives**

The aim of this research has been to investigate the feasibility of integrating lean construction and BIM to improve construction quality in China and to develop a quality-based lean construction and BIM interaction framework during the construction phase. 5 objectives were proposed to address the research aim. The fulfilment of these objectives is discussed below.

#### **Fulfilment of the first objective**

The first objective was to explore and synthesise the current Chinese quality improving requirements. This was accomplished through the literature review, which is presented in Chapter 2. Eight main quality improvement requirements in China (prevention mentality, long-term consideration of quality-oriented mindset change, win-win cooperation, continuous improvement of standardisation, collaborative plans, prioritising customer requirements, continuous information requirement and motivation management) were identified. The fulfilment of the first objective was the foundation of further research on the feasibility of integrating lean construction and BIM to improve Chinese construction quality.

#### **Fulfilment of the second objective**

The second objective was to investigate the quality-based lean construction approaches and quality-based BIM approaches. This was achieved through the literature review and case studies in Chapter 2 and Chapter 4.

The relationships between lean construction and construction quality improvement

were discussed in two aspects. One was quality-based lean construction theory, and the other was quality-based lean construction technique. From the literature review, five quality-based lean construction theories (proactive quality defect prevention culture, conversion to a quality-based mindset, decentralised control- giving authority to workers, customer quality requirements and continuous quality improvement) and four quality-based lean construction techniques (LPS, visual management, kanban and concurrent engineering) were extracted. However, at present, the existing research in this field is not sufficient. There was no evidence of studies that had investigated the relationships between lean construction and construction quality improvement from in a comprehensive manner. It was, therefore, necessary to strengthen the deficiency of the existing research through empirical data. Two quality-based lean construction theories (pull-based quality management and, cooperation and communication) and three quality-based lean construction techniques (5S management, standardisation and first run study) were developed through the use of case studies.

The identified quality-based lean construction theories and techniques were the basis of analysing the quality-based interaction of lean construction and BIM. They also formed the pillars of the interaction framework (see Chapter 5 and 6).

The relationships between BIM and construction quality improvement were identified from two aspects. One was quality-based mechanism, and the other was quality-based BIM application. However, there has been a lack of research on summarising quality-based BIM mechanisms. Thus some of BIM mechanisms were inferred according to the author's intention in existing literature. In addition, there are three quality-based BIM applications identified in the existing literature. Using the case study results, five more quality-based BIM applications can be added to the interaction framework.

The research into the investigation between BIM and construction quality improvement has provided a basis for further research on quality-based interactions between lean construction and BIM as well as developing an interaction framework (see Chapters 5 and 6).

**Fulfilment of the third objective**

The third objective was to analyse the feasibility of integrating lean construction and BIM to improve construction quality considering Chinese quality requirements. This was accomplished through the literature review and case studies. The results were discussed in Chapter 6.

The incentives, limitations and requirements of quality-based lean construction and quality-based BIM were identified in case studies. Using the quality improvement requirements identified in Chapter 2, the feasibility of integrating lean construction and BIM to improve construction quality was discussed in Chapter 6. This feasibility discussion mainly focused on analysing the advantages and disadvantages of quality-based lean construction and quality-based BIM in terms of fulfilling quality requirements. In regard to the results of the discussion, there were four links identified between quality-based lean construction approaches and quality-based BIM approaches, which are that: quality-based BIM contribute directly to quality-based lean construction goals; quality-based BIM contribute indirectly to quality-based lean construction goals; an integrated platform enabled by quality-based BIM contributes directly or indirectly to quality-based lean construction combination goals and quality-based lean construction guide quality-based BIM application.

**Fulfilment of the fourth objective**

The fourth objective was to explore the potential interactions between quality-based lean construction approaches and quality-based BIM approaches. This was accomplished through the results from case studies and surveys in Chapter 4 and Chapter 5; the detail interactions were presented in Chapter 6.

Due to the lack of research focusing on integrating lean construction and BIM to improve construction quality, some of the interactions mentioned in the literature review were inferred according to authors' intention. The potential interactions were mainly identified from the interviews. Interview findings confirmed the importance of integrating lean construction and BIM to improve construction quality. Using the

analysis of the survey results, there were 17 interactions between quality-based lean construction theory and quality-based BIM mechanism. Further to this, 11 interactions between quality-based lean construction technique and quality-based BIM applications were identified.

The findings obtained from the literature review and interviews were used to structure and design the quality-based lean construction and BIM interaction framework, as reported in Chapter 6.

#### **Fulfilment of the fifth objective**

The fifth objective was to develop and validate the interaction framework of lean construction and BIM in terms of Chinese quality improvement. This was accomplished through the framework development and validation.

The framework development was based on the findings from the literature review and the surveys (see Chapter 2 and Chapter 5). There were two interaction levels in the framework, which were a quality-based strategic interaction framework and a quality-based implementation framework. The interaction framework provides a clear integration approach for lean construction and BIM to improve quality. Framework validation was used to refine and examine the suitability of the framework for industry practitioners. Interviews were conducted to validate the framework. According to the respondents, the structure of the framework was clear and the content appropriate to their needs.

The synergies between quality-based lean construction and BIM interactions have been identified in the two-level framework. The holistically integrated utilisation of lean construction and BIM to improve construction quality is required. Therefore, an ‘LC-BIM quality improvement house’ has been proposed and recommended for the Chinese construction industry. The ‘LC-BIM quality improvement house’ is a visualised description of the holistically integrated utilisation of lean construction and BIM to improve construction quality. This could be a new paradigm to improve the quality of Chinese construction.

### **7.3 Research Contributions to Knowledge**

The novelty of this research lies in the development of two-level quality-based lean construction and BIM interaction framework, specific for the Chinese construction phase. To date, it was found that there exists a knowledge gap in the comprehensively researching the quality-based interactions between lean construction and BIM in construction phase. This research extended the range of existing knowledge quality-based lean construction approaches and quality-based BIM approaches. Then the research explored a new research field on comprehensively analysis the interactions between lean construction, BIM and construction quality. In developing the two-level interaction framework, qualitatively approaches were adopted through case study and survey to collect data. The perspectives from the industry theoretically validated the existing literature. However, the research context is limited to Chinese construction phase with specific focus on the large construction companies.

This research has contributed to the industry, which is simplified as follows:

- This research adds to existing knowledge on quality-based lean construction and quality-based BIM by describing the approaches of lean construction improve construction quality and BIM improves construction quality are described respectively from the perspective of construction company. This will assist the construction companies and government in identifying the future development direction of quality-based lean construction approaches and quality-based BIM approaches
- This research provides various interactions between lean construction, BIM and construction quality. Each interaction is an option for construction companies to integrate lean construction and BIM on improving their own project quality
- The case study was conducted in two well-known Chinese companies which provided information-rich data. This helps the industry to understand practical issues of integrating lean construction and BIM on improving construction quality. This research could also be a lesson for other Chinese construction companies
- The clear quality-based relationships between lean construction and BIM in this research could help construction company to understand the practical issues they

- meet on applying lean construction and BIM to improve their construction quality
- The outcomes of this research could provide a foundation knowledge to provide a holistic view on integrating lean construction and BIM to improve Chinese construction quality. It could be used as a guide for construction companies who are not familiar with this field
- The research results could be used for raising awareness of construction company on the importance of integrating lean construction and BIM to improve construction quality. The integrated lean construction and BIM could help the company's construction quality in various aspects
- The outcomes of research could assist the software developer in identifying the future software development direction and solving logical issues in software development

#### **7.4 Research Limitations**

The research limitations are primarily related to the data collection and the interaction framework design and development. These limitations are discussed below.

The time and resource limitations were considered when the number of case studies needed was discussed. The researcher was able to spend time in China collecting data from within construction companies. Despite being a Chinese national, access to case study material was not easy to secure because very few contractors were working with the issues identified in this research. Although one could argue that additional case studies would have made this paper more informative, doing so probably would not have added much to this research given the lack of knowledge of lean construction within contracting organisations in China. While the case studies cannot be seen as representative of the construction industry in China, they do help to illustrate issues that could not be determined via other data collection methods, such as questionnaire surveys.

Similar to the case study research, it was challenging to find a sufficient number of individuals to interview due to the general lack of knowledge and experience relating to lean construction and BIM. This study might have been more representative if all

the interviewees had both lean construction and BIM implementation experience. This is one of the challenges found when combining lean construction and BIM in research on the Chinese construction industry.

The interaction framework was deliberately limited to being used within the construction phase. The other construction phases were not considered in this framework as they were outside the scope of the study. Moreover, the interaction framework was not designed to focus on each specifically integrated implementation, rather on a more comprehensive framework to present available integration directions. Therefore, the framework may currently lack detailed descriptions and examples utilisation for each interaction. Although this is a limitation of the research, it may be a strength for the practitioners using the framework as they can add detail to suit their specific project context. This is an area for future applied research, as noted in the following section.

### **7.5 Recommendations for future Research**

This research developed a two-level lean construction, and BIM integration framework to in-depth understand how integrating lean construction and BIM to improve construction quality. Some recommendations for future research are listed as following.

- The research, as discussed in the limitation of the framework, does not particularly focus on any specific cell in the matrix, instead of providing a holistic view. Therefore, the future work could focus on investigating one interaction in-depth
- The content of the framework is not fixed. With the development of lean construction and BIM, more quality-based interactions between lean construction and BIM could be added in the framework
- Due to the limitation of this research, the future work could be conducted on extending this kind of research to other building phase or throughout the whole building phase
- The outcomes of this research are based on the Chinese construction industry. However, similar research could be done in other countries
- The compatibility in each interaction of lean construction techniques and BIM application on construction quality improving could be a research direction as the

continuation of this research.



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## Appendix

### Appendix 1: Interview template (Case company ZJ)

#### AIM

This interview is a part of PhD research. The aim of this interview is to investigate the current lean theories and techniques on improving construction quality.

This interview contains: Background information, Current quality-based lean construction theories, Current quality-based lean construction techniques and Incentives, limitations and requirements of using lean construction to improve construction quality.

**All information provided will be hold in strict confidence.**

Interview question	Time cost
Background information	5minutes
Current quality-based lean construction theories	20minutes
Current quality-based lean construction techniques	20minutes
Incentives, limitations and requirements of using lean construction to improve construction quality	15minutes
<b>Total duration</b>	<b>1 hour</b>

#### Section 1. Background information

1.1 Please introduce briefly the current application of lean construction in the company?

#### Section 2. Current quality-based lean construction theories

2.1 Based on your experience, what do you think about the potential of ‘proactive quality prevention culture formation’ to improve construction quality?

2.2 Based on your experience, what do you think about the potential of ‘quality-based mindset conversion’ to improve construction quality?

2.3 Based on your experience, what do you think about the potential of ‘decentralised control-giving authority to workers’ to improve construction quality?

2.4 Based on your experience, what do you think about the potential of ‘customer quality requirements’ to improve construction quality?

2.5 Based on your experience, what do you think about the potential of ‘continuous quality improvement’ to improve construction quality?

2.6 Based on your experience, could you mention other lean philosophies that may improve the construction quality?

### **Section 3. Current quality-based lean construction techniques**

3.1 Based on your experience, what do you think about the potential of ‘last planner system’ to improve construction quality?

3.2 Based on your experience, what do you think about the potential of ‘Visual management’ to improve construction quality?

3.3 Based on your experience, what do you think about the potential of ‘Kanban’ to improve construction quality?

3.4 Based on your experience, what do you think about the potential of ‘concurrent engineering’ to improve construction quality?

3.5 Based on your experience, could you mention some other lean techniques that may improve the construction quality?

**Section 4. Incentives, limitations and requirements of using lean construction to improve construction quality** (The Chinese quality improvement requirements could be used as a reference).

4.1 Based on your experience, could you mention some incentives, limitations and requirements of using lean construction to improve construction quality?

**Table: Current quality improvement requirements in China**

<b>No.</b>	<b>Quality improvement requirements</b>
<b>1</b>	Prevention mentality
<b>2</b>	Long-term consideration of interests
<b>3</b>	Win-win cooperation
<b>4</b>	Continuous improvement of standardisation
<b>5</b>	Collaborative plans
<b>6</b>	Customer information requirements
<b>7</b>	Continuous information requirements



## **Appendix 2: Interview template (Case company HY)**

### **AIM**

This interview is a part of PhD research. The aim of this interview is to investigate current BIM mechanisms and applications on improving construction quality.

This interview contains: Background information, Current quality-based BIM mechanisms, Current quality-based BIM applications and Incentives, limitations and requirements of using BIM to improve construction quality.

**All information provided will be hold in strict confidence.**

<b>Interview question</b>	<b>Time cost</b>
Background information	5minutes
Current quality-based BIM mechanisms	20minutes
Current quality-based BIM applications	20minutes
Incentives, limitations and requirements of using BIM to improve construction quality	15minutes
<b>Total</b>	<b>1 hour</b>

### **Section 1. Background information**

1.1 Please introduce briefly the current application of BIM in the company?

### **Section 2. Current quality-based BIM mechanisms**

2.1 Based on your experience, what do you think about the potential of ‘visualisation’ to improve construction quality?

2.2 Based on your experience, what do you think about the potential of ‘simulation and calculation’ to improve construction quality?

2.3 Based on your experience, what do you think about the potential of ‘dynamic’ to improve construction quality?

2.4 Based on your experience, what do you think about the potential of ‘collaboration s’ to improve construction quality?

2.5 Based on your experience, what do you think about the potential of ‘Integration’ to improve



construction quality?

2.6 Based on your experience, what do you think about the potential of ‘coherence’ to improve construction quality?

2.6 Based on your experience, could you mention other quality-based BIM mechanisms that may improve the construction quality?

### **Section 3. Current quality-based BIM applications**

3.1 Based on your experience, what do you think about the potential of ‘BIM-based clash detection’ to improve construction quality?

3.2 Based on your experience, what do you think about the potential of ‘BIM-based construction plan simulation and optimisation’ to improve construction quality?

3.3 Based on your experience, what do you think about the potential of ‘BIM-based quality inspection’ to improve construction quality?

3.4 Based on your experience, could you mention some other BIM applications that may improve the construction quality?

### **Section 4. Incentives, limitations and requirements of using BIM to improve construction quality** (The Chinese quality improvement requirements could be used as a reference.)

4.1 Based on your experience, could you mention some incentives, limitations and requirements of using BIM to improve construction quality?

**Table: Current quality improvement requirements in China**

<b>No.</b>	<b>Quality improvement requirements</b>
<b>1</b>	Prevention mentality
<b>2</b>	Long-term consideration of interests
<b>3</b>	Win-win cooperation
<b>4</b>	Continuous improvement of standardisation
<b>5</b>	Collaborative plans
<b>6</b>	Customer information requirements
<b>7</b>	Continuous information requirements
<b>8</b>	Motivation management

### Appendix 3: Interview template (Survey)

#### AIM

This interview is a part of PhD research. The aim of this interview is to investigate the interactions between quality-based lean construction approaches and quality-based BIM approaches.

This interview contains: ‘background information’, ‘the importance of integrating lean construction and BIM to improve construction quality’, ‘the strategic interactions of lean construction theory’ and ‘BIM mechanism on construction quality’, and ‘the implementation interactions of lean construction technique and BIM application on construction quality’.

**All information provided will be hold in strict confidence.**

<b>Interview question</b>	<b>Time cost</b>
Background information	5minutes
The importance of integrating lean construction and BIM to improve construction quality	10minutes
The strategic interactions of lean construction theory and BIM mechanism on construction quality	25minutes
The implementation interactions of lean construction technique and BIM application on construction quality	25minutes
<b>Total</b>	<b>65minutes</b>

#### **Section 1. Background information**

1.1 Please introduce briefly the current application of lean construction and BIM on quality improvement in the project?

#### **Section 2. The importance of integrating lean construction and BIM to improve construction quality**

2.1 Based on your experience, do you think integrating lean construction and BIM to improve construction quality is important? Why?

#### **Section 3. The strategic interactions of lean construction theory and BIM mechanism on construction quality**

3.1 Could you identify the potential interactions of lean construction theory and BIM mechanism on construction quality through analysing quality-based lean construction theories and quality-based BIM mechanisms.

**Section 4. The implementation interactions of lean construction technique and BIM application on construction quality** (Tables below is used as a reference to facilitate interviewees to understand and answer questions)

4.1 Could you identify the potential interactions of lean construction techniques and BIM applications on construction quality?

**Table: Quality-based philosophies**

No.	Quality-based lean construction theories
1	Proactive quality prevention culture formation
2	Quality-based mindset conversion
3	Decentralized control- giving authority to worker
4	Customer quality requirement
5	Pull-based quality management
6	Continuous quality improvement
7	Cooperation and communication

**Table: Quality-based BIM mechanisms**

No.	Quality-based BIM mechanisms were summarised from literature
1	Visualisation
2	Simulation and calculation
3	Dynamic
4	Collaboration
5	Integration
6	Coherence

**Table: Quality-based lean techniques**

No.	Quality-based lean techniques
1	Last planner system
2	Visual management
3	5S management
4	Kanban
5	Standardisation
6	First run study
7	Concurrent engineering

**Table: Quality-based BIM applications**

No.	Quality-based BIM application
1	BIM-based clash detection
2	BIM-based design joint inspection and technical disclosure
3	BIM-based construction plan simulation and optimisation

- 4 BIM-based design change management
  - 5 BIM-based dynamic template display
  - 6 BIM-based visual construction layout
  - 7 BIM-based quality information management
-

## **Appendix 4: Interview template (Framework validation)**

### **AIM**

This framework validation interview is a part of PhD research. The aim of this interview is to refine and examine the appropriateness of two-level interaction framework.

**All information provided will be hold in strict confidence.**

<b>Interview question</b>	<b>Time cost</b>
Strategic level interaction framework structure validation	15minutes
Strategic level interaction framework content validation	20minutes
Implementation level interaction framework structure validation	15minutes
Implementation level interaction framework content validation	20minutes
Further recommendations	15minutes
<b>Total</b>	<b>85minutes</b>

### **Section 1. Strategic level interaction framework structure validation**

1.1 Based on your experience, what do you think about the structure of strategic level interaction framework

### **Section 2. Strategic level interaction framework content validation**

2.1 Based on your experience, what do you think about the content of strategic level interaction framework

### **Section 3. Implementation level interaction framework structure validation**

3.1 Based on your experience, what do you think about the structure of implementation level interaction framework.

### **Section 4. Implementation level interaction framework content validation**

4.1 Based on your experience, what do you think about the structure of implementation level interaction framework.

**Table: Strategic interaction matrix of quality-based lean construction theory and quality-based BIM mechanism**

Strategic interaction matrix of quality-based lean construction theory and Quality-based BIM mechanism								
Quality-based BIM Mechanism	Quality-based Lean Construction Theory							
		Proactive quality prevention culture formation	Quality-based mindset conversion	Decentralized control-giving authority to worker	Customer quality requirement	Pull-based quality management	Continuous quality improvement	
		1	2	3	4	5	6	
Visualization	a	X	X	X		X		
Simulation and calculation	b	X	X	X				
Dynamic	c			X	X		X	
Collaboration	d		X		X	X		X
Integration	e			X		X		
Coherence	f				X			

**Table: Strategic Interaction Matrix: Explanations of Cell Contents**

Index	Explanation
1-a	The visualisation mechanism of BIM utilises people's visual perceptions to detect defects in a virtual environment. Quality problems can be actively resolved before actual construction begins. Quality is ensured through a proactive prevention approach.
1-b	The simulation and calculation mechanism of BIM helps planners to make reasonable plans. A good construction plan can prevent many quality defects from occurring. Moreover, construction personnel can fully understand the design intent and construction plan before construction using BIM simulation and roaming.
2-a	Visual BIM can improve the workers' quality cognition by allowing them to intuitively view the final construction product. A quality-based mindset can be created through the promotion of quality awareness
2-b	The BIM mechanism of simulation and calculation enhances the quality knowledge of workers by showing them construction techniques in a virtual construction environment. Quality awareness is promoted through BIM simulation, which leads to changes in mindsets
2-d	The BIM mechanism of collaboration helps to promote workers' quality cognition, which leads to the promotion of quality awareness. A quality-based mindset will also gradually take shape as a result

- 3-a BIM provides a simple and direct expression of information through a visualised model. It is beneficial for workers in understanding inspection content quickly and accurately after the authority of quality control is given to them
  - 3-b A mechanism of simulation and calculation enables BIM to provide a way to verify workers' opinions in the process of planning. This ensures the quality of a plan after last planners are involved
  - 3-c The dynamic mechanism enables BIM to transmit up-to-date quality information from the construction site to the office. Managers can identify the latest construction quality trends in a timely manner. This makes decentralised management more reliable
  - 3-e BIM is a platform which can integrate other advanced technologies to promote the ability of quality inspection. The application of BIM improves the quality of workers' inspections
  - 4-c BIM can provide customers with the latest construction information continuously and steadily so that they can make a more accurate judgment of a construction site in order to put forward their quality requirements
  - 4-d BIM provides a collaboration platform that facilitates quality requirement communication between constructors and customers. The information can be transmitted on this platform without hindrance
  - 4-f Coherence mechanisms make BIM adaptable to design changes and facilitate a rapid response to customer quality requirements
  - 5-a The visualisation of BIM provides support for the intuitive representation of quality requirements, which is convenient for workers to understand
  - 5-d BIM can provide a collaboration platform for workers in consecutive construction stages. The quality requirements of the next construction stage are transmitted through the BIM platform
  - 5-e BIM can improve quality inspection abilities by integrating advanced technologies. Quality inspection is carried out from the back to forward between consecutive processes by pulling quality. BIM enhances the implementation of pull-based quality management
  - 6-c BIM is a tool for constantly collecting, processing and storing information. Managers can learn from the lessons and experiences of past projects through the information stored in BIM. Then, the goal of continuous quality improvement can be achieved
  - 7-d Information is transmitted in BIM without hindrance, which increases the efficiency of cooperation. Moreover, the stability of information transmission strengthens cooperation
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**Table: Implementation interaction matrix of quality-based lean construction techniques and quality-based BIM applications**

Implementation interaction matrix of quality-based lean construction techniques and quality-based BIM applications							
Quality-based BIM Applications	Quality-based Lean Construction Technique						
	Last planner system	Visual management	5S management	Kanban	Standardization	First run study	Concurrent engineering
	1)	2)	3)	4)	5)	6)	7)
BIM-based clash detection	I						X
BIM-based design joint inspection and technical explanation	II	X					
BIM-based construction plan simulation and optimization	III	X				X	
BIM-based design change	IV						
BIM-based dynamic template display	V	X			X		
BIM-based visual construction layout	VI		X				
BIM-based quality information management	VII	X		X	X		
BIM-based quality inspection	VIII			X			

**Table: Implementation Interaction Matrix: Explanations of Cell Contents**

Index	Explanation
1)- II	The quality of plans benefits from BIM as joint design inspection, and technical explanation is conducted in a virtual 3D environment. The visualisation of BIM helps planners to understand design intent and facilitates communication and inspection in the design joint inspection phase
1)- III	4D BIM simulation and calculation provide a complete construction procedure in the virtual environment to the planner. The planner can view the plan result intuitively, which makes planner easy to plan
1)- VII	BIM-based quality information management makes BIM a quality information repository. The information requirements of the LPS can be fulfilled by BIM
2)- V	The construction control points, the dynamic construction model, the important construction joints and the construction techniques can be magnified and presented through dynamic templates. Additionally, as BIM-based dynamic templates are easy to make and modify, the implementation of visual management is simplified by adopting the BIM template
3)- VI	BIM can improve the quality of 5S management by providing a visual-based construction layout approach. Temporary storage areas and construction tool placement points can be set up by 5S management with clear boundaries through a BIM-based visual construction layout
4)- VIII	BIM, as an information carrier, can transfer information between consecutive



	construction stages. The requirements of transmitting quality acceptance standards and construction information are fulfilled by BIM
4)-VIII	BIM-based quality inspection enhances workers' ability to detect quality defects. The quality defects can be efficiently prevented from passing to the next construction stage by integrating kanban and BIM-based quality inspection
5)- V	BIM-based dynamic template display presents construction standard regulations through visualised work procedures and virtual standard templates. The workers' understanding of construction techniques and procedures is improved through demonstrating construction work templates in BIM, which helps to achieve construction standardisation
5)-VII	BIM-based information management provides information support for continuous improvement. The standard regulations are continuously updated with the accumulation of construction data and experience
6)- III	The aims of a first-run study are achieved through BIM-based construction plan simulation and optimisation. BIM is a good tool for constantly simulating and optimising a construction plan in a virtual environment, which can facilitate the implementation of a first-run study
7)- I	Concurrent engineering requires the participants to join the design stage as early as possible to improve the constructability of the design and to reduce errors in the construction process. BIM-based clash detection can automatically detect design defects. Its application brings convenience to concurrent engineering.

**Table: Implementation interaction matrix: explanations of cell contents**

Index	Explanation
(1)	The quality of plans benefits from BIM as design joint inspection and technical explanation are conducted in a virtual 3D environment. The visualisation of BIM helps planners to understand design intent and facilitates communication and inspection in the design joint inspection phase
(2)	4D BIM simulation and calculation provide a complete construction procedure in the virtual environment to the planner. The planner can view the plan result intuitively, which makes planner easy to plan
(3)	BIM-based quality information management makes BIM a quality information repository. The information requirements of the LPS can be fulfilled by BIM
(4)	The construction control points, the dynamic construction model, the important construction joints and the construction techniques can be magnified and presented through dynamic templates. Additionally, as BIM-based dynamic templates are easy to make and modify, the implementation of visual management is simplified by adopting the BIM template
(5)	BIM can improve the quality of 5S management by providing a visual-based construction layout approach. Temporary storage areas and construction tool placement points can be set up by 5S management with clear boundaries through a BIM-based visual construction layout
(6)	BIM, as an information carrier, can transfer information between consecutive construction stages. The requirements of transmitting quality acceptance standards and construction information are fulfilled by BIM
(7)	BIM-based quality inspection enhances workers' ability to detect quality defects. The quality defects can be efficiently prevented from passing to the next construction stage by integrating kanban and BIM-based quality inspection
(8)	BIM-based dynamic template display presents construction standard regulations through visualised work procedures and virtual standard templates. The workers'

understanding of construction techniques and procedures is improved through demonstrating construction work templates in BIM, which helps to achieve construction standardisation

- (9) BIM-based information management provides information support for continuous improvement. The standard regulations are continuously updated with the accumulation of construction data and experience
  - (10) The aims of a first-run study are achieved through BIM-based construction plan simulation and optimisation. BIM is a good tool for constantly simulating and optimising a construction plan in a virtual environment, which can facilitate the implementation of a first-run study
  - (11) Concurrent engineering requires the participants to join the design stage as early as possible to improve the constructability of the design and to reduce errors in the construction process. BIM-based clash detection can automatically detect design defects. Its application brings convenience to concurrent engineering.
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